University of Nevada, Reno

Improving Asphalt Concrete Mixtures' Resistance to Studded Tires and Chains Wear

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Abstract

Studded tires and chains are widely used in the United States to provide safer vehicle operating conditions on roads covered with snow or ice. However, they can result in severe damage to the pavement wearing course. The studs and chains wear the pavement surface leaving depressions in the wheel paths which can hold water leading to hydroplaning and significant vehicle dynamics which are both safety issues as well. This thesis examines the effect of studded tires and chains on the open graded friction course mixtures which are the typical wearing course used in Nevada.

Previous research has indicated that the economic impact of studded tire use is significant. While some have confirmed that their use is crucial in mitigating costs, others have affirmed that their use costs outweigh the benefits. Literature has shown that the most representative test to evaluate studded tire wear is the Nordic ball mill abrasion test. Other literature suggests that use of Stone Matrix Asphalt (SMA) mixtures, adopting gradations with larger Nominal Maximum Aggregate Size (NMAS), and using modified binders positively influence mixture resistance to wear.

Different tests were performed on mixtures from five different aggregate sources typically by NDOT. These tests included: Specific gravity and absorption, sieve analysis, sand equivalent, fine aggregate durability, Los Angeles abrasion, Hamburg wheel track test (HWTT) with and without studded tires, Cantabro mass loss and Prall tests. The HWTT was performed under three different conditions: Condition 1 consisted of testing OGFC samples in a dry condition and intermediate temperature; Condition 2 consisted of testing

OGFC samples in a wet condition and high temperature; and Condition 3 consisted of testing OGFC samples containing both dense and OFGC lifts in a condition and intermediate temperature.

Correlation was found between the fine aggregate durability index test and the Prall Abrasion value. Furthermore, significant correlation was found between rut depth resulting from the studded tire at Condition 1 and the rut depth resulting from non-studded tire at Condition 2. Additionally, a relationship was observed between rut depth resulting from studded tire at Condition 2 and the rut depth resulting from non-studded tire at Condition 1.

Based on the findings, it was recommended that the HWTT be performed at low temperature. It was also proposed that a common aggregate gradation be used for all sources to make the comparison between them possible. It was suggested not to consider either the Cantabro or the LA abrasion test as an indicator of studded tire wear resistance. The Prall test, used by Alaska Department of Transportation (AkDOT), appears to distinguish the performance among OGFC mixtures the best among the tests used.

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Chapter 1: Introduction

General Overview

Under severe winter conditions, the use of studded tires and chains becomes imperative to enhance safety by providing sufficient traction on icy roads. However, despite the safety benefits they offer in certain situations, the damage resulting from their usage may outweigh the advantages: the skid resistance ensured by studded tires or chains is counteracted by the wheel path wear resulting from their implementation. In this context, previous literature has indicated that the damage caused by studded tires use causes 47% loss of pavement life (Abaza,2021). For most highway agencies, 0.75-inch rutting depth is the criterion for repair which is less than the 1-inch depth created by studded tires within 6 years (Anderson et al.,2009). When a stud or a chain passes on the pavement, raveling occurs, fine aggregates wear off, and the binder-aggregate skeleton degrades resulting in a rutting in the wheel path. These ruts generated on the road could be filled with water causing hydroplaning and loss of skid resistance posing significant safety concerns. This creates a vicious loop, while studded tires and chains are employed to improve safety, their usage also introduces safety issues.

Studded tires are widely used in the United States with different regulations shown in Table 1. Nevada Department of Transportation (NDOT) is one of those states that allows the use of studded tires and chains during a specific period of the year. NDOT is known for its adoption of open grade friction course (OGFC) with a PG 64-28 NV binder as the pavement wearing course on all national highway system routes in the state. There are three NDOT routes that pass over the Sierra Nevada Mountains in northwestern Nevada which are particularly susceptible to studded tire and chain wear. There are 3 sources of aggregates and 1 supplier of binder used to produce OGFC used on these routes.

Table 1. State Studded Tire Regulations (Bahadori et al.,2018)

State	Regulation	State	Regulation
Alabama	Prohibited	Montana	Oct 1 to May 31
Alaska	Sept 15 to May 1	Nebraska	Nov 1 to April 3
Arizona	Oct1 to May 3	Nevada	Oct 1 to April 30
Arkansas	Nov 1 to April 1	New Hampshire	No Restrictions
California	Nov 1 to April 30	New Jersey	Nov 15 to April 3
Colorado	No Restriction	New Mexico	No restrictions
Connecticut	Nov 15 to April 30	New York	Oct 16 to April 30
Delaware	Oct 15 to April 15	North Carolina	No restrictions
DC	Oct 15 to April 15	North Dakota	Oct 15 to April 15
Florida	Prohibited	Ohio	Nov1 to April 15
Georgia	Safety requirement	Oklahoma	Nov1 to April 3
Hawaii	Prohibited	Oregon	Nov1 to April 3
Idaho	Oct 1 to April 30	Pennsylvania	Nov1 to April 15
Illinois	Prohibited	Rhode Island	Nov1 to April 3
Indiana	Oct 1 to May 3	South Carolina	Oct 1 to April 30
Iowa	Nov 1 to April 3	South Dakota	Oct 1 to April 30
Kansas	Nov 1 to April 15	Tennessee	Oct 1 to April 15
Kentucky	No restrictions	Texas	Prohibited
Louisiana	Prohibited	Utah	Oct 15 to March 31
Maine	Oct 1 to April 30	Vermont	No restrictions
Maryland	Prohibited	Virginia	Oct 15 to April 15
Massachusetts	Nov 2 to April 30	Washington	Nov 2 to March 31
Michigan	Prohibited	West Virginia	Nov 1 to April 15
Minnesota	Prohibited	Wisconsin	Prohibited
Mississippi	Prohibited	Wyoming	No Restrictions

Compared to conventional rutting, studded tires, and chain wear produce wheel path ruts that are different in appearance and cause than plastic deformation, as shown in Figure 1. One Alaska Department of Transportation (AkDOT) study showed that stud-related rutting occurring in winter is far more severe than permanent deformation rutting occurring in the summer (Iskra,2018). This finding is illustrated in Figure 2. A challenging fact is that the solutions mitigating the permanent deformation could increase the rutting caused by wear. Avoiding permanent deformation consists of reducing the asphalt binder content, which in turn, increases the potential of raveling due to chain wear by weakening the bonds between aggregate and binder.

Figure 1. HMA Permanent Deformation due to Trucks (WSDOT, 2008)

Figure 2. HMA Raveling due to Studded Tires (WSDOT, 2008)

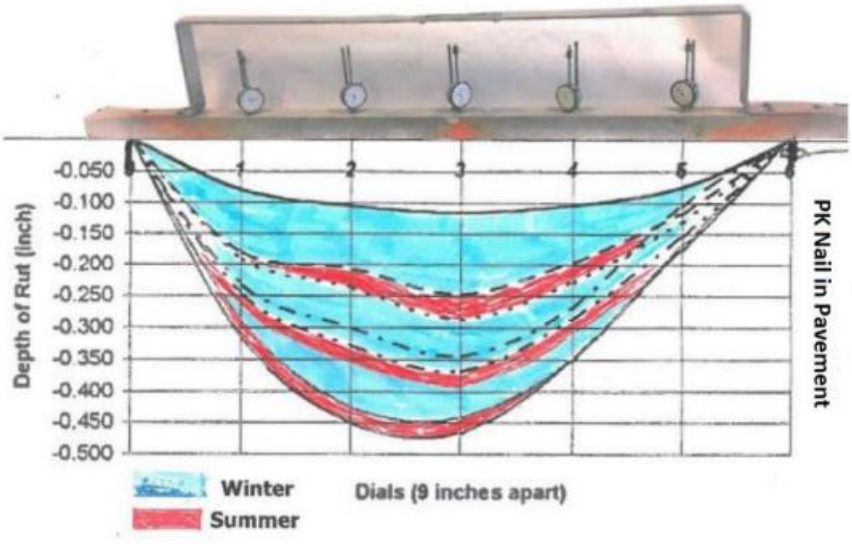

Figure 3. Rut Depth Progression (Iskra,2018)

While permanent deformation rutting can be induced by various layers within the pavement structure, rutting caused by studded tires is confined to the surface layer. Several U.S. states have the surface riding layer as an open-graded friction course (OGFC) as a surface wearing course as shown in Figure 3. OGFC is a permeable thin layer applied at the surface of the pavement structure to minimize noise, increase friction and provide adequate drainage. The aggregate gradation used for these permeable layers can vary among different states. The NDOT aggregate gradation specification for OGFC in this study is illustrated in Table 2 (NDOT Silver Book,2014)

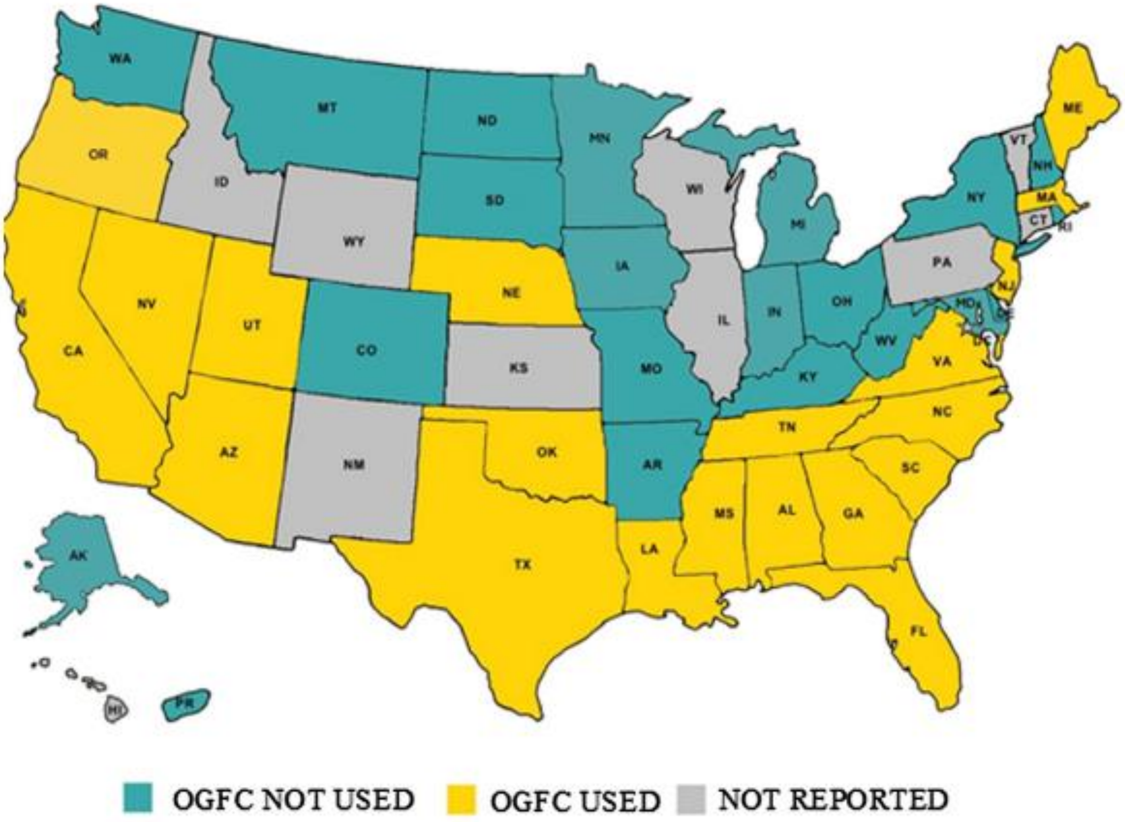

Figure 4. Use of OGFC mixtures by state highway agencies in 2015 (F. Gu et al.,2018)

Table 2. NDOT open-graded gradation specifications (NDOT Silver Book,2014)

Sieve Size	Open-Graded Friction Course Specification Range Percent Passing (%)
1/2”	100
3/8”	95-100
No.4	40-65
No.16	12-22
No.200	0-5

The cost associated with the rutting created by studded tires and chains is significant and considered a drawback to their application. Therefore, producing wear-resistant asphalt mixes is key to benefit from the studded tires without jeopardizing the pavement's life.

Previous research has shown that studded tire and chain wear is influenced by several factors such as vehicle speed, stud type, and traffic volume. Some studies address these factors and show that using lightweight studs, decreasing vehicle speed, and reducing traffic volume could reduce pavement wear. In Anchorage, a lightweight stud consists of a light metal composite or polymer covering with a tungsten carbide tip. These studs weigh less than 1.1 g for passenger cars, 2.3 g for vans, and 3.0 g for trucks. They are available with single or double flanges. On the other hand, a conventional stud is made up of a steel covering with a tungsten carbide tip and usually weighs around 1.9 g for passenger cars, 2.4 g for vans, and 2.8 – 9.3 g for trucks. Conventional studs have typically one flange and they consist of steel jacket with tungsten carbide pin. The mass of these studs is 1.9 g for passenger cars, 2.4 g for vans and 2.8 – 9.3 g for trucks (Zubeck et al.,2004).

However, using lightweight studs, decreasing vehicle speed, and reducing the traffic volume could not be definitive solutions to solve the problem. The strength and resistance of a mixture to distress are derived from its two main components: aggregate and asphalt binder. Any change in these factors may lead to an alteration in the mixture's performance. Current literature has categorized previous research into three areas: economic impact, influence of aggregate gradation, binder type, and mixture properties on wear resistance.

Research Objectives

The objective of this research is to evaluate typical aggregates and mixtures used in NDOT

District 2 to determine their resistance to tire chains and studded tires. To accomplish this objective, the following tasks were implemented:

- Assess Lab Mixed Lab Compacted (LMLC) mixtures using by performing Prall, Cantabro and Hamburg Wheel Track Test.
- Measure aggregate source properties based on current NDOT specifications.
- Determine the mineralogy of the aggregates.
- Investigate the correlation between aggregate properties and performance in both the Prall test and the Hamburg Wheel Track Test.

Scope of Work

To assess the resistance of NDOT OGFC mixtures to chain and studded tire wear, a series of laboratory testing on typical aggregates and mixtures used in NDOT District 2 was conducted. The aggregate sources all those that supply NDOT mixtures in the Reno/ Carson City Area, specifically the Q&D Construction Mustang Quarry, Granite Construction Lockwood Quarry, Western Nevada Materials Lockwood Quarry and Basaltic Material from Mustang Quarry in Western Nevada. The Granite Construction Brunswick Canyon Quarry was also evaluated for future use as an OGFC. The testing is divided into three sets: Aggregate Testing, LMLC Performance testing and Field Mixed Field Compacted (FMFC) or Field Cores Performance Testing.

Chapter 2: Literature Review

Economic impact:

Wheel path rutting caused by studded tire and chain wear leads to significant repair and maintenance costs. AkDOT spends $13.7 million annually in resurfacing costs, while only collecting $0.32 million in studded tires fees (Abaza et al., 2021). The cost of the studded tire damage is 42 times what AkDOT collects in fees. In this context, state agencies, European highway agencies and Canadian provinces have found that high pavement repair costs are associated with studded tire use. The use of studded tires is a double-edged sword: Although they provide safety benefits, they are associated with an increased cost due to excessive pavement wear. Estimates by the Washington Department of Transportation (WSDOT) indicated an annual cost between $7.8 million and $11.3 million due to pavement wear damage. (Estimate of Annual Studded Tire Damage to Asphalt Pavements, W.S.DOT. Transportation, 2012). Likewise, the findings of a new economic analysis performed in AKDOT showed that the estimated total cost of mitigating studded tire damage over the next 20 years to be $203.2 million in 2019 (Abaza et al.,2021). Moreover, a significant decrease in studded-tire wear became a need (Xiaojun et al. 2020). This reduction serves multiple purposes, including saving repair costs, ensuring safer transportation, and improving pavement performance. (Xiaojun et al. 2020). Wen and Bhusal also affirmed an urgent need to reduce studded tire wear to reduce pavement repair costs(Wen and Bhusal, 2014). The state of Oregon estimated its annual studded tire damage cost to be around $7 million in 2000 (Malik,2000). A more recent study done in Oregon performed an 11-year projection of expenditures for repairing studded tire damage to be around $44.2 million by 2022. AkDOT has, historically, spent $5 million annually to repair stud tire related pavement damage (Barter and Johnson ,1996). Moreover, on the socio-economic level and due to the dust produced by the wear, studded tire use increases the medical care cost linked with respiratory infections or other illnesses including throat irritation, headache, nausea, asthma; and shortened life spans (Evans et al., 1987).

In contrast, some studies have shown that studded tires play a role in mitigating costs by ensuring safe driving conditions. As an example, an economic analysis in Japan showed an increase of $137 million in the annual cost when studded tire use was banned (Asano et al. 2002). A significant portion of the rise in cost was linked to an increase in traffic accidents caused by icy and slippery roads. This led to a drastic augmentation in road user expenses due to longer travel times resulting from slower vehicle speeds and to a rise in tire replacements because non-studded tires wear out faster than studded ones. However, the economic assessment did not consider the impacts on human health, as establishing a direct link between dust pollution and negative health effects proved challenging. This study demonstrated that the observed increase was attributable to rising accident costs, an increased demand for surface applications to improve traction. (e.g., sand, salt) and an increased user cost (Asano et al. 2002). Similarly, Estonians reported the prevention of 20 deaths in 1998, due to studded tire use, where the average death cost was estimated at $300,000 (Sürje, 1999). It is true that pavement wear caused by studs is costly, yet the savings in pavement repair provided by their ban could be entirely counterbalanced by the increased costs of surface applications (Zubeck et al.,2004).

Overall, two divergent results were obtained from review of previous research. While some studies showed the necessity of limiting the use of studded tires to control costs, others encouraged use of studded tires as a means to reduce costs by reducing safety risks.

Aggregate influence on wear resistance

1. Aggregate hardness effect on wear resistance

Studies discussed in this section highlight the role hard aggregates play in mitigating studded tire wear and in prolonging pavement life. A research study performed in Nordic countries indicated that the use of metamorphic hard aggregates reduces studded tire wear by a factor of 3 to 5 (Johnson et.al,2000). Based on the Nordic abrasion value, Scandinavian countries showed that aggregate hardness has positively affected pavement performance in terms of wear resistance (Douglas et. al, 2004). This study emphasized the significance of hard aggregates in extending the lifespan of pavements. Predictive performance models forecasting the effect of using hard aggregates on the wear rutting reduction in Juneau and Anchorage were developed based on AKDOT data. Figure 5 shows the positive effect of hard aggregate use in resisting studded tire rutting distress. In his study, Pavey used the Prall test as a simulator of studded tire wear, on both FMFC and LMLC (Pavey,2020). The results revealed that hard aggregates exhibit effective wear-resistant behavior. LMLC samples included different types of aggregate, binder content, and void content levels (Pavey,2020). The effect of the binder and air voids will be discussed in the following section.

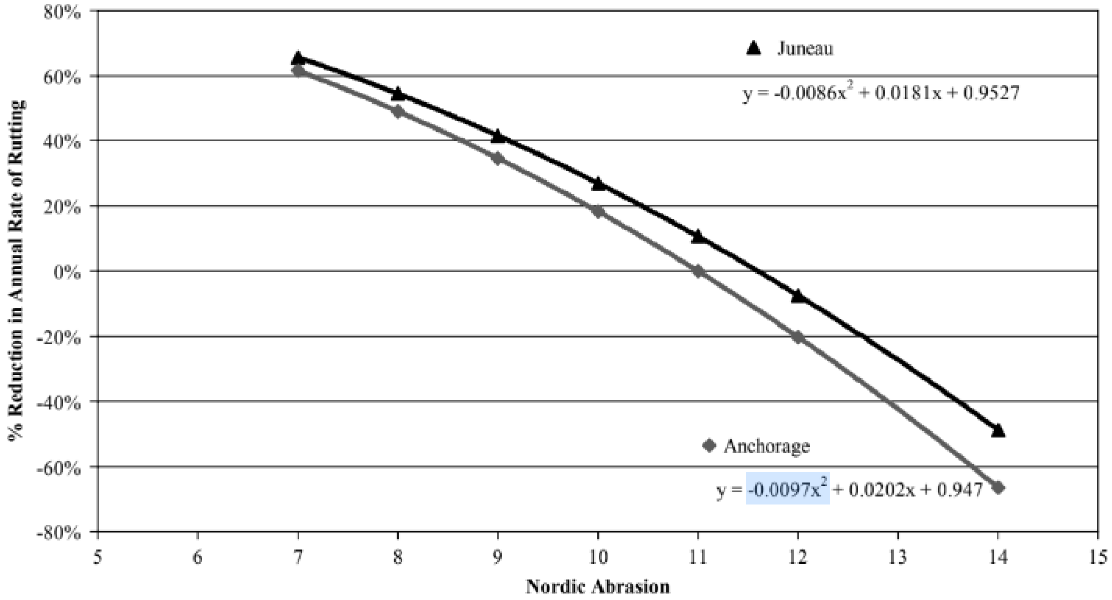

Figure 5. Percent reduction in annual rate of rutting versus the Nordic abrasion value in Juneau and Anchorage (Douglas et al.,2004)

In conclusion, these studies indicate that use of hard aggregates reduces pavement wear rutting due to studded tires.

2. Mineralogy of hard aggregates and test identifying hardness:

The mineralogy of the aggregate used is a factor that affects the behavior of a given asphalt concrete mixture. Based on the findings presented in Section 1, hard aggregates showed a positive impact on studded wear resistance. Consequently, it is a must to define hard aggregates based on mineralogy and to determine lab testing that detects this aggregate characteristic.

Several tests have been used to assess aggregate hardness. However, based on several studies the Nordic ball mill test proved to correlate to hardness the best (Douglas et al.,2004; Hunt,2001; R&M CONSULTANTS, INC.,2013). In her study, Hunt compared three lab tests, Los Angeles Abrasion test, Nordic ball mill test and the micro-deval test, with the aim of evaluating the latter. The Nordic abrasion test was the most indicative in terms of wear abrasion and hardness. When compared to the Los Angeles abrasion, the micro-Deval showed similar behavior. However, when Nordic ball mill test was introduced, it showed a stronger correlation with aggregate hardness (Hunt, 2021). Hunt's finding about the Los Angeles abrasion test was affirmed by another study where the Los Angeles abrasion test did not exhibit a correlation with hardness and wear resistance (Malik et. al. 2000). Moreover, when a hard aggregate source location study was conducted, the Nordic ball mill test was used as a reference of aggregate hardness (R&M CONSULTANTS, INC.,2013). This study identified tests that examine the aggregate hardness by selecting the Nordic abrasion value of 10 or less as a criterion. Los Angeles abrasion, Degradation, Specific gravity and absorption, and Unconfined Compressive Strength (UCS) tests were compared to the Nordic ball mill test and as shown in Table 3. The best correlation was found with the Unconfined Compressive Strength test (R&M CONSULTANTS, INC.,2013)

The Los Angeles abrasion test did not show differences between different rocks. To be able to get reliable results from this test, source performance history should be known which is not always available. Aggregates with high degradation values are more suitable for usage as hard aggregates than those with low values. However, this test is not necessarily measuring hardness but rather the durability of material aggregates. The reason for this is that some aggregates may break down into finer particles, yet not to an extent that results in low degradation values. Consequently, this test is considered a general indicator of hardness only. The Specific gravity and absorption, it did not show a significant correlation with hardness since some rocks have attractive absorption and specific gravity values yet have low hardness and durability. This is not the case for the UCS where a strong relationship between UCS and the Nordic Ball mill abrasion test affirmed a good correlation for this test with hardness. (R&M CONSULTANTS, INC.,2013). Moreover, The Los Angeles abrasion test did not show a significant correlation to studded tire wear, which is not true for the Nordic ball mill test (Johnson et al 2000).

Table 3.Reliability of selected tests for predicting Nordic abrasion value (R&M CONSULTANTS, INC.,2013)

Test	Reliability for Predicting Nordic Abrasion Value
LA Abrasion (ASTM C 131)	Moderate
Degradation (ATM 313)	Low to Moderate
Specific Gravity (ASTM C 128)	Low
Unconfined Compressive Strength (ASTM D7012)	Good

Hardness is a characteristic associated with coarse material retained on the number 4 sieve. In terms of mineralogy, hard aggregates are defined as those having the following characteristics: rock weathering, origin, type, grain-size, presence of foliation or mineral orientation, and alteration or degree of metamorphism (R&M CONSULTANTS,2013). R&M CONSULTANTS found that fine-grained rock without foliation and mineral orientation are igneous or metamorphic such as quartzite amphibolite, hornfels, basalt, and metamorphosed volcanics (R&M CONSULTANTS,2013).

Weathering is discussed in this literature as being a prominent factor in classifying aggregates as hard or soft. Resisting this natural process is an important characteristic of hard aggregates. Aggregates that are readily and extensively weathered were not considered to be hard. Table 4 illustrates weathering grades and hard aggregates production.

Table 4. Weathering and alteration grades (R&M CONSULTANTS, INC.,2013)

Grade	**Term**	**Description**	**Hard Aggregate Production**
I	Fresh	No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surfaces	Possible, Depends on rock hardness characteristics
II	Slightly weathered	Discoloration indicates weathering of rock material and discontinuity surfaces. All the rock material may be discolored by weathering and may be somewhat weaker externally than in its fresh condition	Possible, Depends on rock hardness characteristics
III	Moderately weathered	Less than half the rock material is decomposed and/or disintegrated to a soil. Fresh or discolored rock is present either as a continuous framework or as corestones	Not suitable
IV	Highly weathered	More than half the rock material is decomposed and/or disintegrated to a soil. Fresh or discolored rock is present as a discontinuous framework or as corestones	Not suitable
V	Completely weathered	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact	Not suitable
VI	Residual Soil	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported	Not suitable

Another set of factors discussed in the research included grain size, porosity, and grain shape. By affecting the surface area of the interlocking bond forces at mineral grain-to-grain contacts, those factors control rock hardness. The higher the surface area, the harder the aggregate. A decrease in porosity and in size of mineral grains increases the grain surface area of contact. Also, a change from irregular grains to angular ones increases the surface area as well (R&M CONSULTANTS,2013).

The origin and type of rock also affect the categorization of hard aggregates. To highlight the importance of these factors the research illustrated a comparison between the mylonite found in Norway and that found in Alaska. Due to unique depositional histories and tectonic forces, the mylonite in Norway is characterized as a hard, fine-grained rock. In contrast, mylonite in Alaska which had experienced more intense shearing forces and had not undergone sufficient consolidation to be classified as hard. Hence, the same type of aggregate can behave as hard in one location and soft in another. This study showed that fine-grained igneous rocks, such as basalt and dolerite, are harder than coarse-grained rocks such as gabbro, diorite, and granite since their grains are held together more tightly. Sedimentary rocks are considered to have low hardness, since they are highly porous, thus their grains are less tightly held together. For Metamorphic rock development of foliations plays a role in classifying. Such rocks as hard or not, those with low grade metamorphism and no foliations are hard (R&M CONSULTANTS,2013). Other studies also addressed that volcanic and metamorphic rocks are harder and have been used to resist studded tires wear (Johnson & Pavey,2000).

Influence of gradation type on wear resistance (Gradation types/properties)

In an effort to mitigate the progression of pavement wear, extensive laboratory and field testing was conducted to develop wear-resistant pavement mixes. One mixture modification is related to gradation.

1. SMA gradation:

Most studies have suggested the use of Stone Matrix Asphalt (SMA) to be the best gradation type in resisting wear. SMA mixtures, used in high traffic locations, consist of gap-graded gradations that have proved to perform well in several pavement distresses including fatigue cracking, permanent deformation and studded tire wear. It is used in states where extreme weather fluctuations occur.

SMA and coarser aggregates mixtures have better wear resistance than conventional hot mix asphalt (Wen et.al, 2016). Moreover, SMA provides better resistance in both permanent deformation and studded tire wear, where a study performed in Alaska showed that dense graded mixture with 20 mm maximum aggregate size wore 10% faster than SMA mixture with 16 mm maximum aggregate size (Zubeck et al., 2004). This is also related to the maximum size, which will be discussed in the next section (Section 3). In addition, SMA played an important role where the studded tire wear was found to be about 6 g/vehicle-km for good SMA type mixes and 37 g/vehicle-km for dense graded asphalt concrete with local aggregates (Gustafson, 1997). On the contrary, the Stone Matrix Asphalt (SMA) gradation, when subjected to the impact of studded tires, experiences rapid pavement wear. This occurs as the binder matrix and the larger aggregates of the rock-on-rock Hot Mix Asphalt (HMA) structure become susceptible to raveling, resulting in deterioration over a short period of time (Pavey, 2022). The Parks Highway in Wasilla Alaska was constructed in 2005 with an SMA mixture as a wearing course layer. A 2” wear depth was found in 2020 (Pavey, 2022). Likewise, SMA does not exhibit any advantage in terms of resistance to wear from studded tires as it does not outperform conventional HMA mixture in this aspect (Wen et al. 2016).

2. Open-graded gradation:

OGFC is a type of wearing course containing a high void content, a high asphalt percentage and a relatively large amount of coarse aggregates. They are used to reduce pavement noise and to ensure better pavement drainage by providing higher permeability. However, the efficacy of these benefits diminishes over time as the (OGFC experiences wear and becomes clogged with debris. This process can significantly diminish the benefits of OGFC.

Previous literature showed that OGFC has not performed well in terms of studded tire wear resistance. After testing several mixes using the Prall test, it was found that OGFC gradation had the worst performance in wear resistance compared to other types of gradations (Xiajun et al., 2020). Experience in Washington and Arizona states showed high studded tires wear associated with the use of OGFC and that a successful OGFC experience was only noticed in states where studded tires were not used (Muench et al.,2011). This study also indicated that the pavement performance life of OGFC is limited to 2 to 3 years only when studded tires are used, eliminating the noise reduction benefits associated with the open gradation (Muench et al.,2011).

3. Aggregate size effect on wear resistance

Aggregate is a factor believed to have a significant effect on wear resistance. As mentioned in the previous section, the larger the aggregate size of the mixture, the lower the wear (Zubeck et al.,2004). Coarser aggregates and specifically stones have better wear resistance compared to fine aggregates (Wen et al.,2016). Increased wear loss was noticed for the 4.75-mm NMAS mix, compared to the 12.5 mm NMAS mix due to the larger amount of fine aggregates eroded easily by studs (Wen et al.,2016).

Influence of binder type on wear resistance (Binder properties)

The second type of modification is related to the asphalt binder. In the literature, two binder modifications were identified. Either an addition of modifiers to a binder or a change in the performance grade (PG). In Pavey's study, the Prall test performed on the lab samples with varying binder contents and types indicated that increasing binder contents, adopting highly polymer modified binders, and using softer binders with a lower end performance grade improve wear resistance (Pavey, 2022). However, when comparing PG 58-28 binder mix with PG 70-28 binder mix using the studded tire simulator shown in Figure 6, it was found that increasing the high temperature binder PG significantly improved resistance to studded tire wear (Wen and Bhusal, 2014). Conversely, another study showed that changing the asphalt binder PG assisted in studded wear improvement, but the change was not statistically significant (Xiaojun et al.,2020).

Figure 6. Studded tires simulator (Wen & Buhsal,2014)

The addition of crumb-rubber to asphalt binder, provides resistance to studded tires wear (Takallou et al.,1987). Moreover, using modified binder improves wear resistance (Arrojo, 2000). A 50% reduction in wear rate was noticed after using crumb-rubber modified asphalt mix compared with conventional asphalt mix (Zubeck et al., 2004). Crumb rubber advantage in terms of wear resistance was also highlighted in Abaza and Dahms study where laboratory performance research was conducted by Alaska DOT&PF and a reduction of wear was noticed with the use of crumb-rubber (Abaza & Dahms,2021). On the contrary, a study showed that the addition of crumb-rubber was not a good option for the improvement of studded-tire wear resistance (Bahadori et al.2018).

In conclusion, binder modifications have a significant impact on the wear resistance, however, a lack of consensus in the results of various studies exists, leaving the concept of an optimal binder modification unclear.

Mixture properties

In previous sections, mixture components were discussed separately and their effect on the wear resistance was presented independently. However, undoubtedly these components are highly interrelated and work together to provide the mix with its unique properties.

Attempting to reach a wear resistant mix without compromising the pavement overall performance, a comprehensive testing program was conducted by adopting three control mixtures based on previous literature and specifications (Xiajun et. al,2020). These mixtures had different Nominal Maximum Aggregate Size (NMAS), gradation, binder content and crumb-rubber content. To measure the studded tire wear resistance of the mixes produced, the Asphalt Pavement Analyzer (APA) machine associated with studded tires was used where 8000 cycles were applied on each specimen .As mentioned in Section 2, one of the conclusions of this study was that the open gradation did not show a good wear resistance Another conclusion related to the number of cycles adopted in this study was that 8,000 cycles were not enough to induce a significant difference in the results between different mixtures. In addition, several other findings were based on the mix components interaction between each other. Despite the contribution of the crumb rubber addition to the wear resistance, it was shown that it is a good option only for 4.75-mm NMAS mixes which is not the case for coarser mixtures. Another set of combinations is related to fine aggregates and binder PG where it was proven that simultaneously increasing the fine aggregates amount and bumping the PG grade improved the wear resistance (Xiajun et. al,2020).

Regarding the binder content effect, it was proved that an increase in asphalt binder content improved studded-tire wear resistance for both coarse dense graded and dense graded 4.75-mm NMAS mixtures, but it must be carefully added since it worsened the permanent deformation. Therefore, a good solution is to reduce studded tire wear where rutting is not the prevalent distress (Bahadori et al.,2018).

All the studies discussed try to identify resistant mixes to studded tires wear, however little is known about the state of Nevada where the wearing course is constituted of open gradation and crumb rubber modification is not encouraged. Hence, the purpose of this study is to evaluate typical aggregates and mixtures used in NDOT Districts 2 to determine their resistance to tire chain/studded tire wear.

Chapter 3: Experimental Plan

The experimental plan adopted is shown in Figure 4. Five aggregate tests were considered performed: Specific Gravity and Absorption, Sieve Analysis, Sand Equivalent, Fine Aggregate Durability, and Los Angeles Abrasion. For performance tests were used: Hamburg Wheel Track Test (HWTT) with and without studded tires, Cantabro Test, and Prall Test. The Cantabro test was performed on field cores sample, as the OGFC portion of the field cores was very thin.

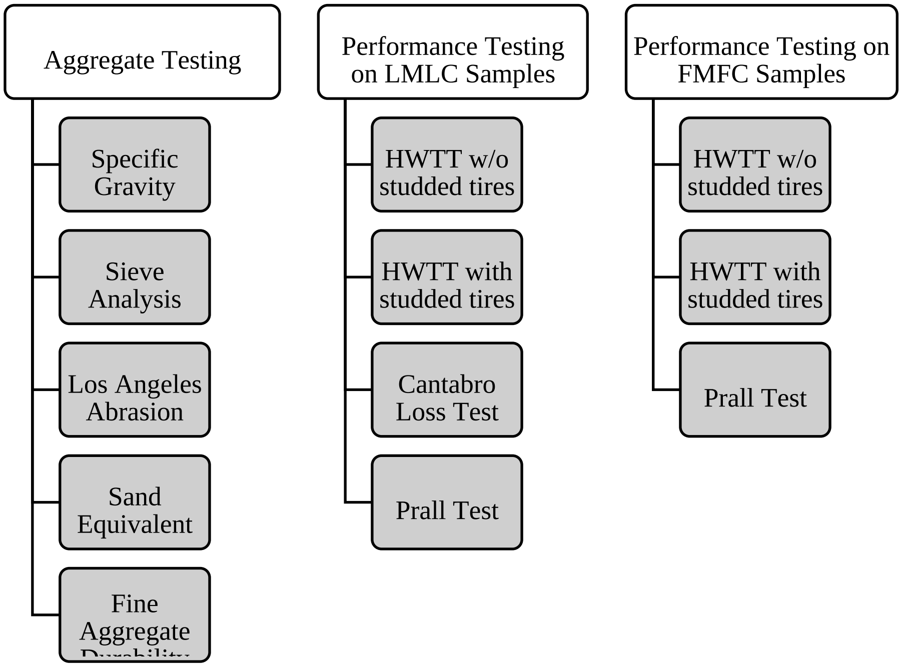

Figure 7. Experimental Plan

Aggregate Testing

1. Specific Gravity and Absorption

Specific gravity is the ratio of the weight of a certain volume of aggregates to the weight of an equivalent volume of water, while apparent specific gravity refers to the relative density of the solid material excluding pore space. Absorption values are crucial for calculating the change in aggregate mass caused by water absorbed in aggregate pore spaces, compared to the dry condition. Measured absorption values were compared to the mix design values and then used to determine the amount of water that was added in the lime marination process.

a. AASHTO T85 – Standard Test Method for Specific Gravity and Absorption of Coarse Aggregates (AASHTO, 2022)

AASHTO T85 is used to determine the specific gravity and percent water absorption of coarse aggregates To achieve a saturated surface dry (SSD) condition, aggregates were soaked for 15 to 19 hours, and then a damp towel was utilized to reduce the aggregate surface moisture to the SSD condition, which is apparent when the sheen on the aggregate surface transitions from shiny to just dull before measuring the aggregate weight underwater and dry after weights.

b. AASHTO T84 – Specific Gravity and Absorption of Fine Aggregates (AASHTO, 2022)

The AASHTO T84 is used to determine the specific gravity and absorption and of fine aggregates. A fine material sample weighing 1000 grams was obtained according to the blend gradation. This sample was soaked with a minimum of 6% water by the dry aggregate weight for a duration of 15 to 19 hours. After soaking, the sample was dried until it reached the SSD condition, confirmed when the material exhibited a slight slump in the cone test. Subsequently, 500 grams of the SSD sample were introduced into a pycnometer and agitated for 15 minutes to release any trapped air. The weights of the pycnometer in both wet and dry conditions were then determined.

2. Sieve Analysis

The sieve analysis test was performed to confirm the gradation of the aggregates from each source.

a. AASHTO T11 – Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing (AASHTO, 2022)

AASHTO T11 is used to determine the content of material finer than a No. 200 sieve in aggregates using the washing method. In this process, water was used to remove clay particles and other aggregate components, commonly referred to as wet sieving. Wet sieving is a more effective method for eliminating finer particles when compared to dry sieving and is conducted as a preliminary step before the AASHTO T27 test.

b. AASHTO T27 – Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates (AASHTO, 2022)

AASHTO T27 is used to determine the particle size distribution of both fine and coarse aggregates through the process of sieving. The results are used to determine compliance with both NDOT open-graded gradation specifications and the NDOT mix design gradation.

3. Los Angeles Abrasion

a. AASHTO T96 – Resistance to Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles Machine (AASHTO,2022)

The Los Angeles Abrasion test is used to determine the toughness and abrasion resistance of aggregates, with a resistance to wear. Grading C, outlined in Table 5, was adopted, leading to the use of 8 steel spheres weighing a total of 3330 grams. The procedure involved placing the washed aggregate in the Los Angeles Abrasion machine, along with the steel spheres, and running the machine for 500 revolutions. The rotational speed was maintained between 30 to 33 revolution per minutes (rpm). The resulting sample was sieving over a No.12 sieve and was subsequently washed. The mass loss was then determined as a percentage of the initial sample weight.

Table 5. Gradings of Los Angeles Abrasion Test Samples

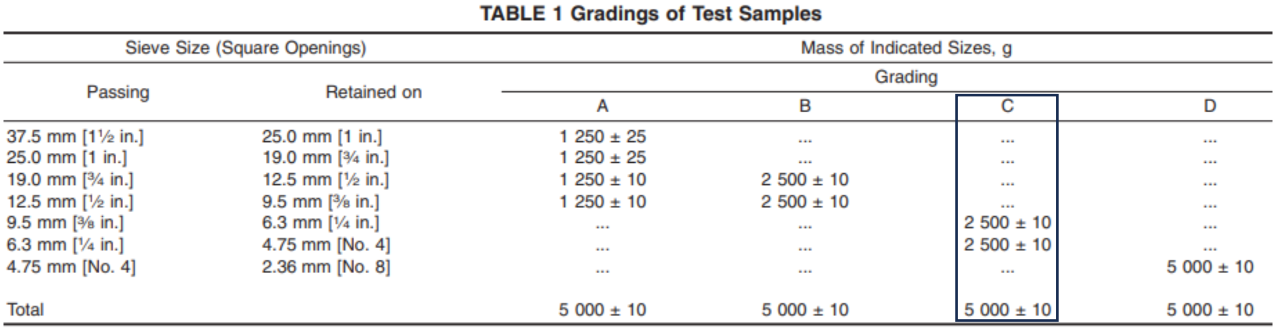

TABLE 1 Gradings of Test Samples

Sieve Size (Square Openings)		Mass of Indicated Sizes, g			
		Grading			
Passing	Retained on	A	B	C	D
37.5 mm [1½ in.]	25.0 mm [1 in.]	1 250 ± 25	...	...	...
25.0 mm [1 in.]	19.0 mm [¾ in.]	1 250 ± 25	...	...	...
19.0 mm [¾ in.]	12.5 mm [½ in.]	1 250 ± 10	2 500 ± 10	...	...
12.5 mm [½ in.]	9.5 mm [⅜ in.]	1 250 ± 10	2 500 ± 10	...	...
9.5 mm [⅜ in.]	6.3 mm [¼ in.]	...	...	2 500 ± 10	...
6.3 mm [¼ in.]	4.75 mm [No. 4]	...	...	2 500 ± 10	...
4.75 mm [No. 4]	2.36 mm [No. 8]	...	...	...	5 000 ± 10
Total		5 000 ± 10	5 000 ± 10	5 000 ± 10	5 000 ± 10

4. Sand Equivalent

a. AASHTO T176 – Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test (AASHTO,2022)

The purpose of this test is to provide an assessment of the relative amounts of fine dust, or clay-like substances present in soils or graded aggregates. It determines the proportion of detrimental fines in the portion that passes through the 4.75-mm (No. 4) sieve in soils or graded aggregates. This procedure involved preparing 1000 to 1500 grams of material that passes through the No. 4 sieve. The material was placed in a cylinder containing a solution of calcium chloride. Subsequently, the sample was subjected to mechanical agitation for

45 seconds, followed by 20 minutes of sedimentation. The sand and clay readings were noted using a weighted assembly after the sedimentation period had passed. The sand equivalent value was calculated by dividing the sand reading by the clay reading. The higher the sand equivalent index the cleaner the aggregates.

5. Fine Aggregate Durability

a. ASTM D3744 – Standard Test Method for Aggregate Durability Index (ASTM, 2022)

This method involves determining an aggregate's durability index, which gives an indication of the fine aggregate's resistance to the production of clay-like fines when subjected to mechanical degradation. The testing procedure is similar to the sand equivalent test, with some modifications to the testing process. These modifications consists of washing the fine aggregates before testing, and to extend the agitation period to 10 minutes.

6. Lime Marination

All the aggregate samples that were to be mixed with binder, were treated with 1.5% hydrated lime, which is used to improve the resistance of the OGFC to stripping. The process consisted of bring the aggregates 2%+ over the absorption capacity, mixing them for 2 minutes, followed by mixing them with 1.5% lime by dry weight of aggregates for 3 additional minutes, and then a marination period of for 48 hours before use.

Air Voids Testing

Theoretical Maximum Specific Gravity

a. AASHTO T209 - Theoretical Maximum Specific Gravity (Gmm) and Density of Asphalt Mixtures (AASHTO, 2022)

The theoretical maximum specific gravity, considering zero air voids, is used in combination with bulk specific gravity to determine the air voids in compacted samples. AASHTO T209 specifies a minimum sample size of 1500 g for an NMAS of 9.5 mm. The asphalt mixture was aged for 16 hours at 140°F, and then manually separated to remove all the clumps. Subsequently, the sample was subjected to a vacuum process (27.5 ± 2.5 mmHg) with agitation before being immersed in water. The binder content of the samples tested was not equivalent to the optimum bitumen ratio specified in the mix design. This is because the optimum bitumen ratio for open-graded mixtures was high leading to a rich mix full of clumps that are hard to separate. Therefore a 5% bitumen ratio was adopted for all the sources ensuring that proper coating was reached for all aggregates. The Gmm at the optimum bitumen ratio was then calculated using the constant Gse. The formulas used for the calculation are shown below.

7. Bulk Specific Gravity

a. AASHTO T331 – Bulk Specific Gravity (Gmb) and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method (AASHTO, 2022)

Since open-graded mixtures have a high air void level, it was crucial to adopt the convenient method to determine the bulk specific gravity. AASHTO T331 describes the method of determining the Gmb of open graded specimens. The test consists of sealing the sample in a bag and applying vacuum. As a result five weight measurements were obtained to: the weight of dry specimen,the weight of sealing bag, the weight of the sealed specimen under water and finally the weight of the dry specimen after removal from the sealed bag.

Performance Testing

1. Hamburg Wheel Track Test

a. AASHTO T324 – Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA) (AASHTO,2022)

The Hamburg Wheel-Track Test is usually used to determine the rutting and stripping potential of asphalt concrete mixtures. In this study was used to assess the resistance of the OGFC to studded tire wear. Both studded and non-studded wheels were used as shown in Figure 1. Since only the wear resistance is of interest in this study, the non-studded tire was used as a control to account for mixtures' permanent deformation. This test was run in three different conditions shown in Table 6.

Table 6. Hamburg Wheel Track Test Conditions

Condition	Structure	Wheels Load	Sample Height	Dry/Wet	Temperature (°C)
1	Open Graded	705±4.5 N	60±2 mm	Dry	23
2	Open Graded			Wet	50
3	Open Graded + Dense Graded			Dry	23

Figure 8. Hamburg Wheel Track Test Setup

b. Laser Texture Measurement

To identify the impact of the studded tire on the surface texture of the asphalt concrete mixtures, the AMES Laser Texture Machine was used. The mean profile depth was measured for all the specimens before and after the Hamburg wheel track test. Three measurements were recorded for each sample.

2. Cantabro Loss Test

a. Tex-245-F – Cantabro Loss ("Standard Specification for Construction of Highways, Streets and Bridges," TEX, 2021)

This procedure assesses the abrasion loss in compacted specimens of hot-mix asphalt (HMA). It involves measuring the disintegration of compacted samples using the Los

Angeles Abrasion machine. The percentage of weight loss, known as Cantabro loss, is an indicator of asphalt concrete mixtures' durability and is linked to both the quantity and quality of the asphalt binder. In this study, it was assessed as an indicator of wear resistance. The test consisted of placing the sample in the Los Angeles abrasion machine and running it at 300 revolutions. The mass loss in terms of the initial weight of the sample is finally determined.

3. Prall Test

a. ATM 420 – Abrasion of HMA Mix by the Prall Method (Alaska Department of Transportation and Public Facilities, 2022)

The Prall test intends to simulate the studded tire wear effect on asphalt concrete mixtures. A cylindrical specimen, with a diameter of 100±1 mm and a length of 30±1 mm, is cooled to a temperature of 5±1°C. Subsequently, the specimen was subjected to a 15-minute abrasion test using 40 steel spheres. The resulting decrease in volume, measured in cm3, is recorded as the abrasion value. Both LMLC and FMFC samples were sent to AkDOT for testing as the apparatus used is exclusively owned by AkDOT.

Chapter 4: Material Characterization and Sample Preparation

Material Characterization

One source of binder was used for this study having a performance grade of PG 64-28 NV, which is the standard binder used in NDOT District 2. The gradation of each source of aggregates is shown in Figure 9 as per the NDOT JMF. Bitumen ratios adopted were based on JMFs provided by NDOT and shown in Table 7, except for the Mustang Western Nevada source. To capture the effect of the aggregate mineralogy on mixture performance, the Mustang Western Nevada source gradation and binder content were the same as the Mustang Q&D. Five different aggregate sources of aggregates were used.

Table 7. Bitumen Ratio Used for Each Aggregate Source

Aggregate Source	Bitumen Ratio (%)
Mustang Q&D	6.5
Mustang Western Nevada	6.5
Spanish Springs	6.7
Brunswick	6.8
Lockwood	7.1

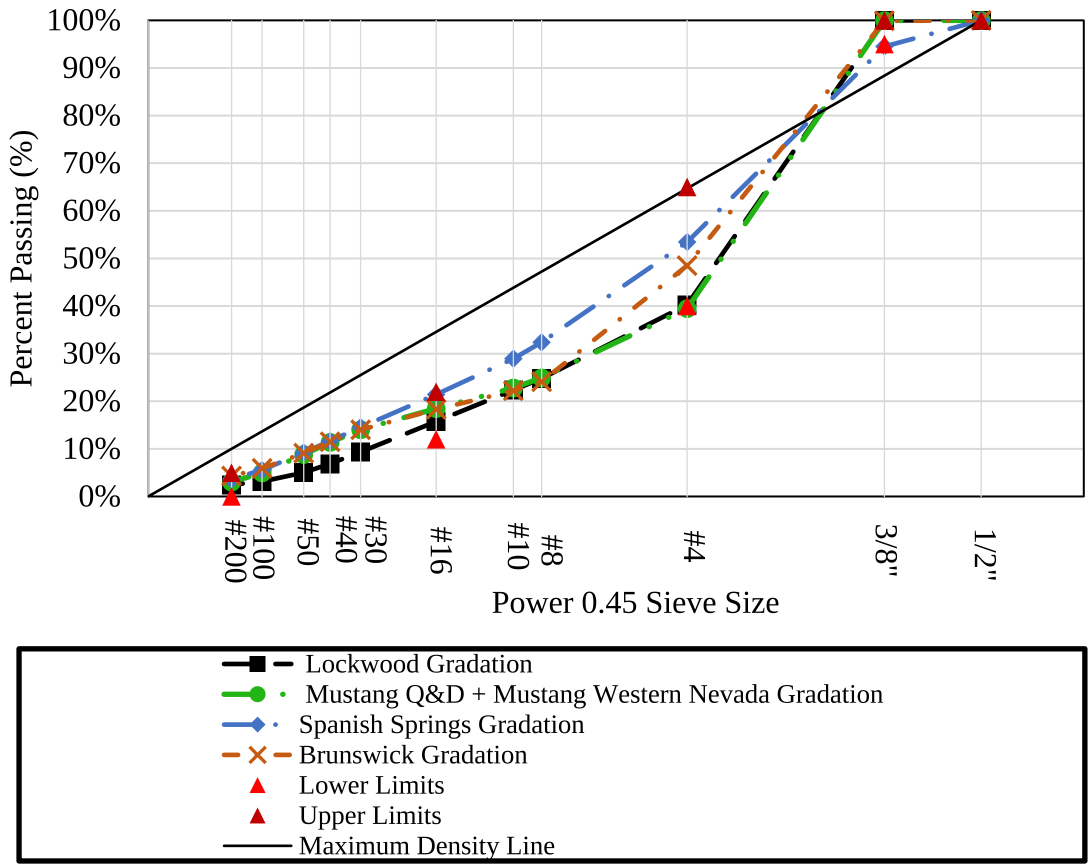

Figure 9. Aggregate Gradations for all Sources

As for the dense graded material used for condition 3 in the Hamburg wheel track test mentioned in section 1 above, was sampled from Brunswick pit.

Sample Preparation

In a full factorial experiment designed to evaluate the influence of aggregate gradation and effective asphalt content to compare the performance of aggregate sources, common volumetric properties of compacted test specimens would be targeted. However, due to the major difference in the gradations between the aggregate sources, it was challenging to reach a common air void level. Efforts made to achieve this revealed a very wide range in the number of SGC gyrations required, with very high numbers of gyrations needed for both Mustang and Lockwood samples. To determine the impact of this high number of gyrations on the gradation of the trial samples, extraction was performed, and the final gradation was determined and compared to the initial one. The trial samples consisted of a HWTT sample for Lockwood and Mustang Q&D sources.

After noticing a difference in the gradation as shown in Figure 10 and Figure 11, it was agreed to compact the samples to the SGC locking point (Polaczyk et al., 2019).

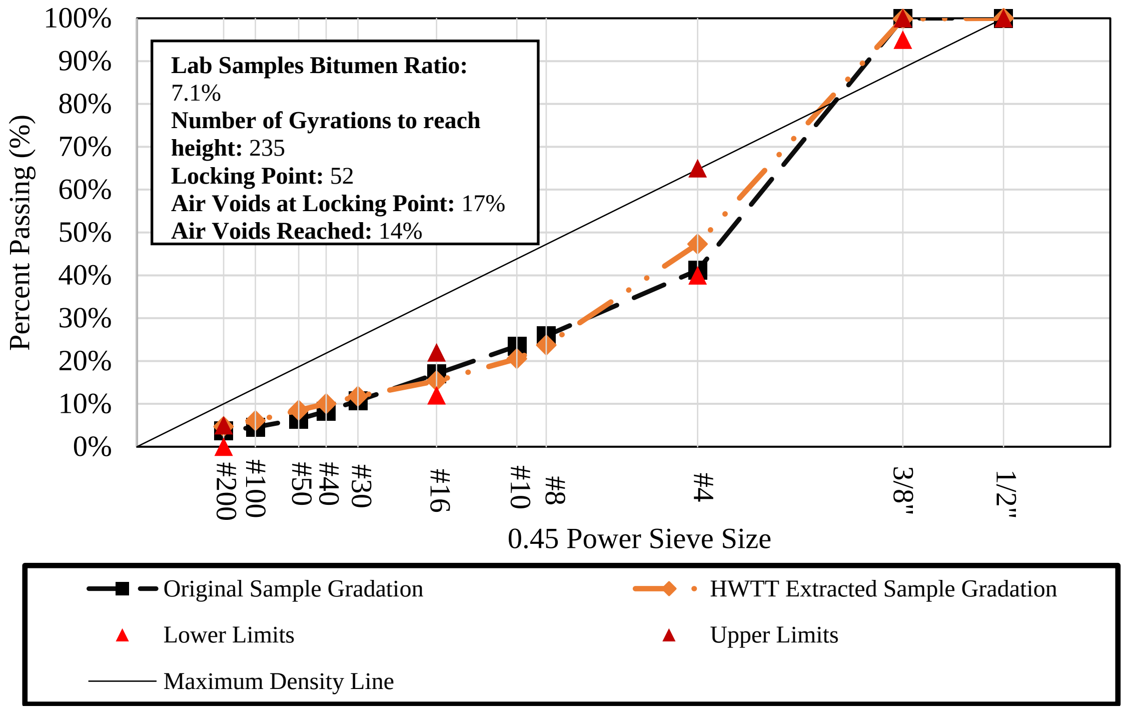

Figure 10. Lockwood HWTT Aggregate Gradation Before and After Compaction

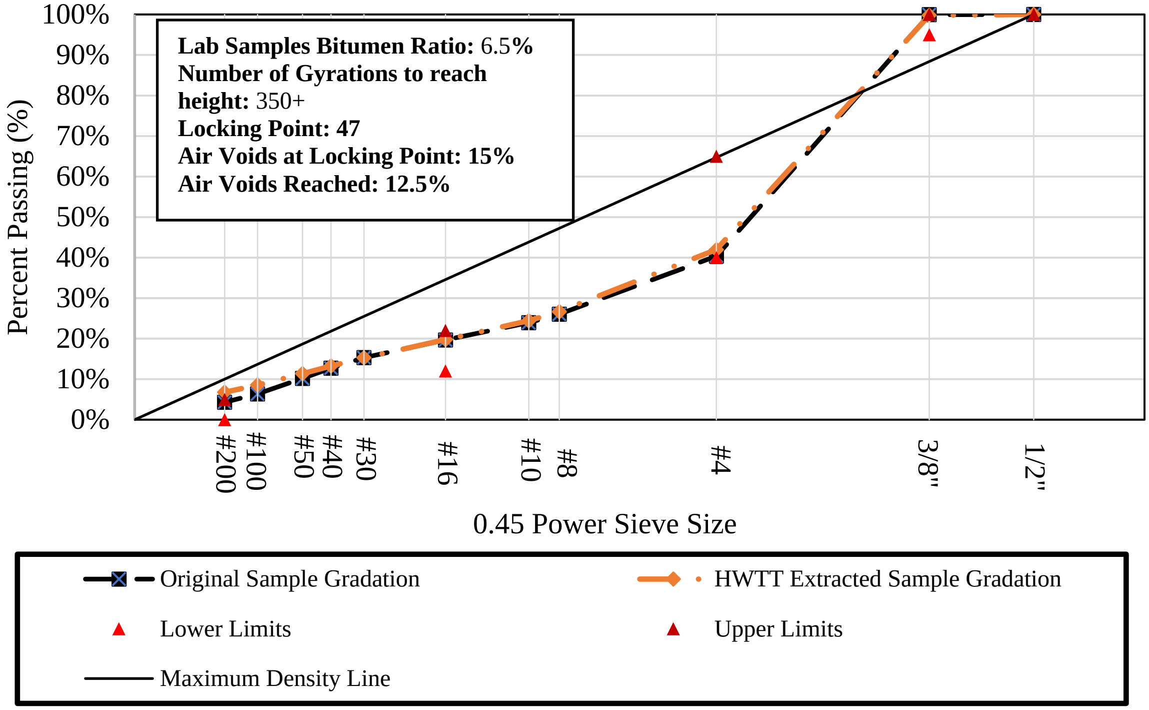

Figure 11. Lockwood HWTT Aggregate Gradation Before and After Compaction

The locking point refers to the stage in the compaction process of asphalt mixture wherein the aggregate structure achieves stability. Beyond this stage, additional compaction does not notably enhance the density of the mixture and can potentially damage the aggregate particles. In this study, the locking point is defined as the point at which three consecutive gyrations produce no change in the specimen's height (Polaczyk et al., 2019). The samples for all the performance tests were compacted to the locking point while meeting the height criteria for each test. The locking points for each aggregate source and test method are shown in Table 8.

The HWTT performed on OGFC over dense graded mixture relied on a unique sample preparation method. Typically, a tack coat is applied before placing a thin overlay to improve the bond between the existing surface and the overlay, which enhances the structural strength of the pavement by limiting slippage between layers and increases the durability of the overlay by reducing the risk of delamination (Tack Coat Guidelines, 2009). In this study, applying a tack coat between the OGFC and dense graded layers was impractical due to the excessive number of gyrations required to compact the dense graded layer using the gyratory compactor. To prevent over-compaction, the bottom layer (dense graded) was initially compacted up to 10 gyrations and then the OGFC sample was added and the whole sample was then compacted to a height of 62 mm, conforming with the HWTT height criteria. Both layers were heated during the compaction process, and insights from the NCHRP 09-64 project indicate that the binder from the heated top layer played a significant role in enhancing the bond between the layers (Hand et. al., 2023). Consequently, the binder in the hot top layer mix served as the bonding agent to the bottom layer, effectively achieving the bonding of the top layer to the bottom layer through the hot binder in the mix.

Table 8. Locking Point for Each Performance Test Sample

Source	Test	Locking point
Mustang Q&D	HWTT/Prall Test	47
	Cantabro	83
Lockwood	HWTT/Prall Test	52
	Cantabro	87
Spanish Springs	HWTT/Prall Test	48
	Cantabro	93
Mustang Western Nevada	HWTT/Prall Test	49
	Cantabro	91
Brunswick	HWTT/Prall Test	47
	Cantabro	97

Field Cores

Field cores were obtained for Mustang Q&D, Lockwood, and Spanish Springs from three different locations. It should be noted that these cores were taken from the shoulder of the road. The air void level was determined for the open-graded lift of the cores. The core in-place air voids information are shown in Table 9. Figure 12 shows the mix design gradation of the field cores.

Table 9. Field Cores Information

Aggregate Source	Project Location	Air Void of Open Graded Lift (%)
Mustang Q&D	US 395 Douglas County	17
Lockwood	US 95 Lyon County	10
Spanish Springs	US 395 Douglas County	8

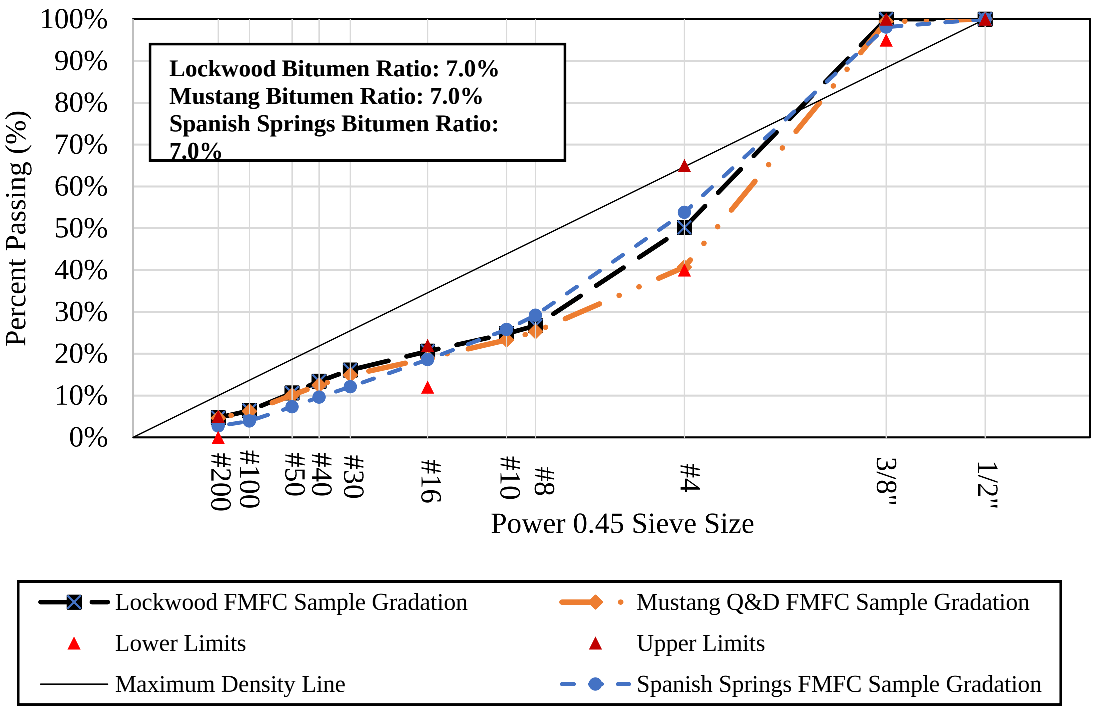

Figure 12. FMFC Cores Gradations

Chapter 5: Results and Discussion

Aggregate Testing

1. AASHTO T11; AASHTO T27 - Sieve Analysis (AASHTO, 2022)

Both a wet and dry sieve analysis were performed for each source to confirm the gradation provided by the most recent NDOT mix design. The results of the sieve analysis for each source are shown in Figure 13. The gradation used for each test was the one in the NDOT mix design and they are shown in Figure 14 for each aggregate source. The sieve analysis confirmed the gradations of the mix designs with slight differences on the #4 sieve. The Lockwood and Mustang sources had the coarsest gradations compared to the Brunswick and Spanish Springs sources.

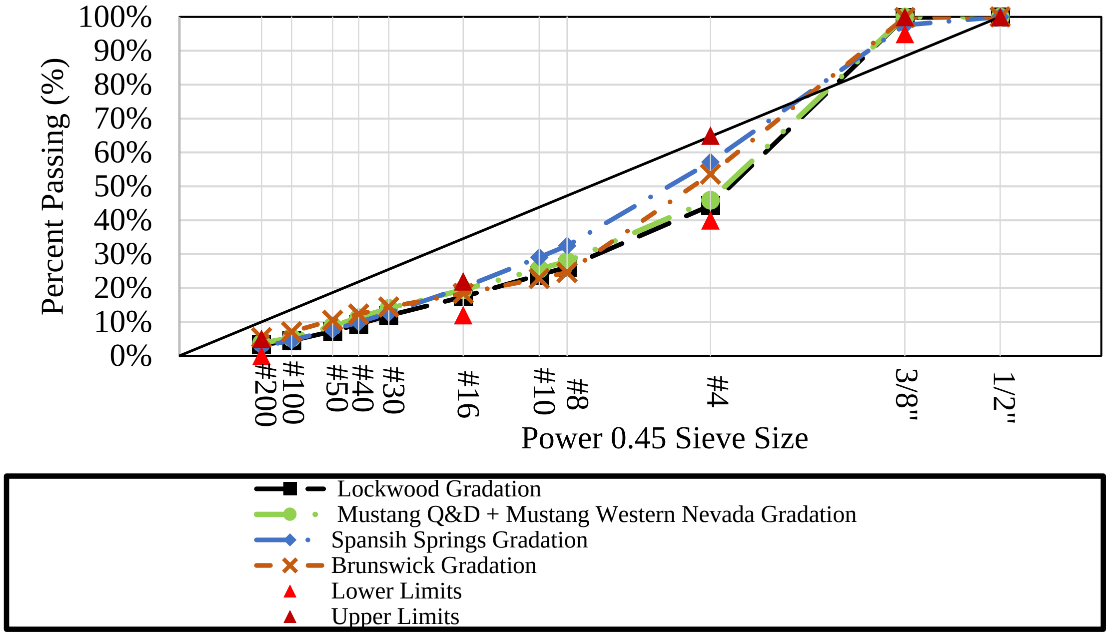

Figure 13. Sieve Analysis Test Results for all Sources.

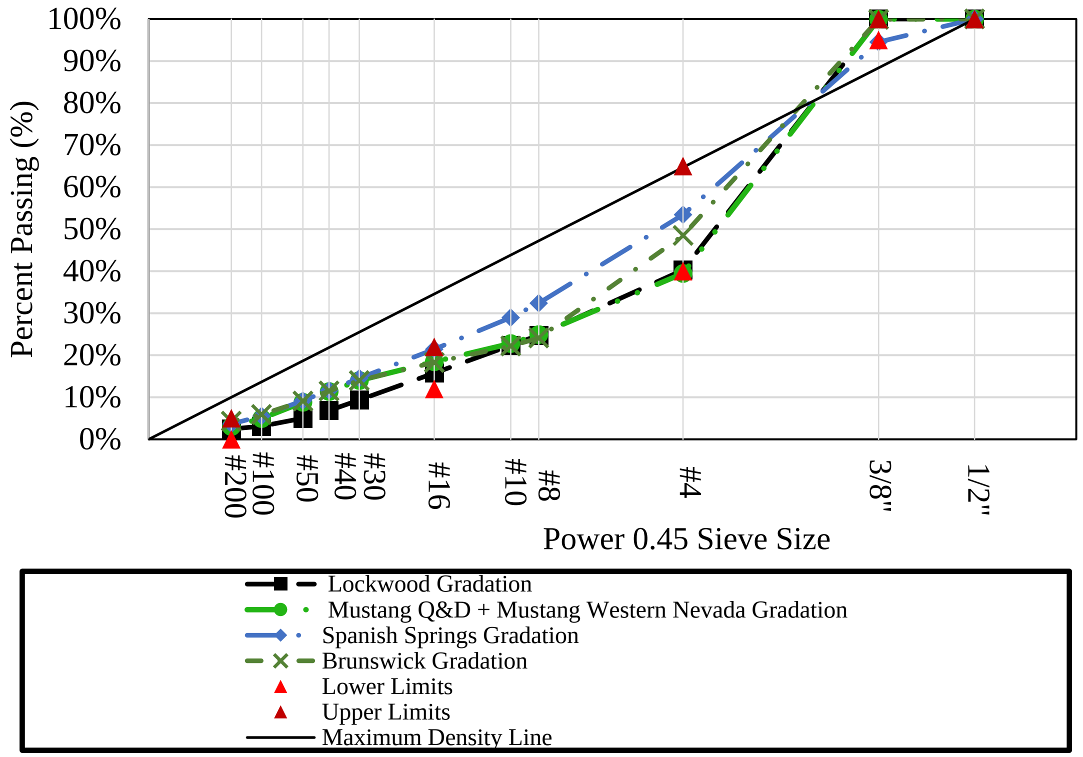

Figure 14. NDOT Mix Designs Gradations for all Sources.

2. AASHTO T84; AASHTO T85 - Specific Gravity and Absorption (AASHTO, 2022)

The specific gravities and absorptions of the aggregates from each source were determined and are summarized in Table 10. The most absorptive aggregates among all sources are the Lockwood aggregates while the least absorptive aggregates belong to the Spanish Springs Source. All the aggregate sources passed both the specific gravity and absorption criteria in the NDOT Standard Specifications (Silver Book, 2014).

Table 10. Specific gravities and absorption for all sources (Silver Book, 2014)

Source	Specific Gravity	NDOT Criteria	Absorption (%)	NDOT Criteria (%)	Pass/Fail NDOT Criteria
Mustang Q&D	2.640	≤ 2.95	2.12	≤ 4	Pass
Lockwood	2.518		3.07		
Spanish Springs	2.630		1.16		
Mustang Western Nevada	2.561		2.18		
Brunswick	2.694		2.36		

3. AASHTO T176 - Sand Equivalent (AASHTO, 2022)

The Sand Equivalent test was performed on all the aggregate sources and the results are shown in Table 11. The Mustang Q&D aggregates are the cleanest while Brunswick aggregates are the dirtiest among all the sources. However, Sand Equivalent values obtained are relatively high for all the aggregate sources. Finally, there is no NDOT criteria for the Sand Equivalent values of open-graded aggregates.

Table 11. Sand Equivalent Test Results

Source	Sand Equivalent (%)
Mustang Q&D	85
Lockwood	73
Spanish Springs	84
Mustang Western Nevada	71
Brunswick	70

4. ASTM D3744 - Fine Aggregate Durability (ASTM, 2022)

The fine aggregate durability index determined for each source is shown in Table 3. Mustang Q&D fine aggregates are the most durable while Brunswick are the least durable. However, it should be mentioned that after performing the analysis of variance table (ANOVA), it was concluded that the results of different sources are not statistically different. This indicates that, aggregates durability is similar for all different sources.

Table 12. Fine Aggregate Durability Test Results

Source	Fine Aggregate Durability Index (%)
Mustang Q&D	95
Lockwood	75
Spanish Springs	87
Mustang Western Nevada	85
Brunswick	69

5. AASHTO T96 - Los Angeles Abrasion (AASHTO, 2022)

The Los Angeles abrasion values were determined and shown in Table 13. All the aggregates passed the percentage wear set by NDOT (Silver Book, 2014). The aggregates having the highest toughness and durability are the Mustang Q&D aggregates while the ones with the lowest toughness and durability are Spanish Springs aggregates. It is worth noting that all the aggregates pass the NDOT criteria for this test and it is not surprising that the Granitic Spanish Springs source has higher loss in the LAR than the basalt and andesite sources due to the crystalline structure of these different aggregates.

Table 13. Los Angeles Abrasion Test Results

Source	Mustang Q&D	Lockwood	Spanish Springs	Mustang Western Nevada	Brunswick
LA Abrasion (%)	14.3	18.8	21.7	20.6	18.1
NDOT Criteria (%)	≤ 37				
Pass/Fail	Pass				

Air Voids Testing

1. AASHTO T209 - Maximum Theoretical Specific Gravity (AASHTO, 2022)

The maximum theoretical specific gravity of the mixtures was determined at a 5% bitumen ratio for all the aggregate sources. The values of the maximum theoretical specific gravities at the optimum bitumen ratio are shown in Table 14.

Table 14. Maximum Theoretical Gravity Test Results

Source	Mustang Q&D	Lockwood	Spanish Springs	Mustang Western Nevada	Brunswick
Gmm at 5% Bitumen Ratio	2.52	2.436	2.475	2.461	2.589
Optimum Bitumen Ratio (%)	6.5	7.1	6.7	6.5	6.8
Gmm at Optimum Bitumen Ratio	2.469	2.372	2.421	2.414	2.524

Performance Testing

1. Cantabro Test (Tex-245-F) (TxDOT,2021)

The Cantabro test results are shown in Table 15. Lockwood and Brunswick mixtures showed the best performance while Mustang Western Nevada mixtures showed the worst performance.

Table 15. Cantabro Test Results

Source	Mustang Q&D	Lockwood	Spanish Springs	Mustang Western Nevada	Brunswick
Cantabro Mass Loss(%)	1.3	0.6	0.9	1.9	0.6
Air Voids (%)	10.7	10.9	2.7	10.3	9.0
Bitumen Ratio (%)	6.5	7.1	6.7	6.5	6.8

Figure 15 shows the Cantabro test results were also plotted with the Los Angeles abrasion values for each source to determine if any correlation exists between these tests. Figure 4 showed does not show correlation between those two tests (R^2=0.0024).

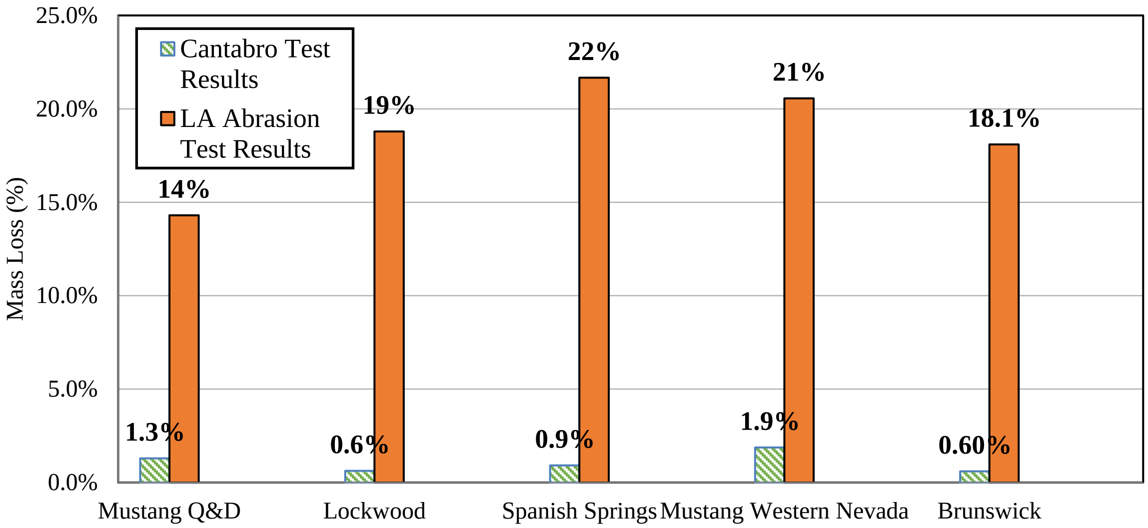

Figure 15. Cantabro Mass Loss and Los Angeles Abrasion Test Results

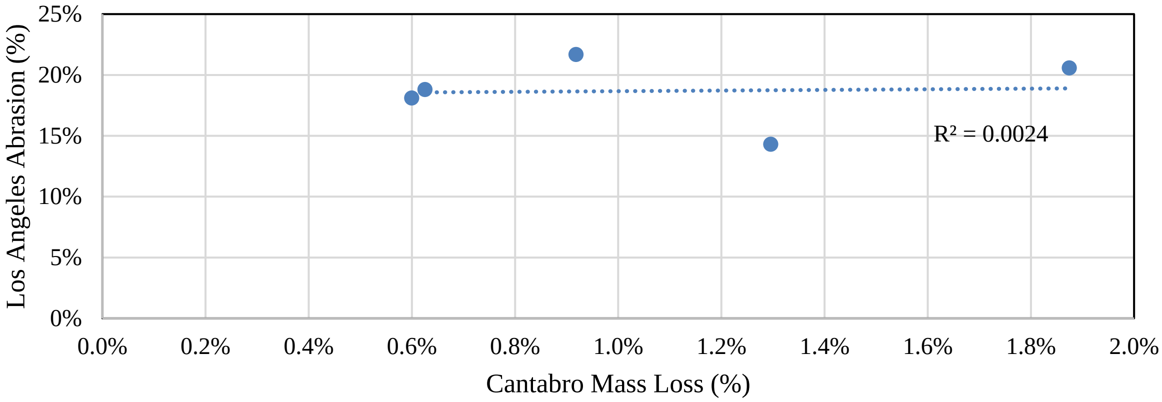

Figure 16. Correlation Between Cantabro Mass Loss Results and Los Angeles Abrasion Test Results

2. Hamburg Wheel Track Test (AASHTO T324)

a. Condition 1

The HWTT results for Condition 1 are shown in Table 7. The studded tire resulted in greater rut depths compared to the non-studded tire for all the aggregate sources. Based on the results, it could be concluded that all sources performed similarly although they have different binder contents, gradations, air voids and mineralogies. Pictures 17 through 36 show the condition of samples after testing for both studded and non-studded tires. Table 16 shows a summary of the test conditions and the results. Figure 37 illustrates the Rut Depth versus the number of passes curve for each aggregate source. The samples were barely damaged, and this was expected as the test was performed at intermediate temperature in a dry (no water) condition.

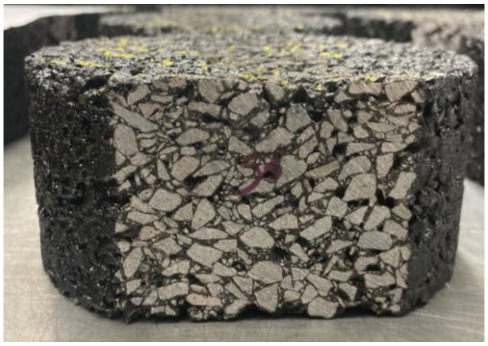

Figure 17. Mustang Q&D Tested Sample under Studded Tire Side View (Condition 1)

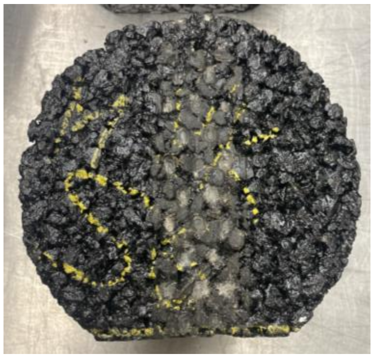

Figure 18. Mustang Q&D Tested Sample under Studded Tire Top View (Condition 1)

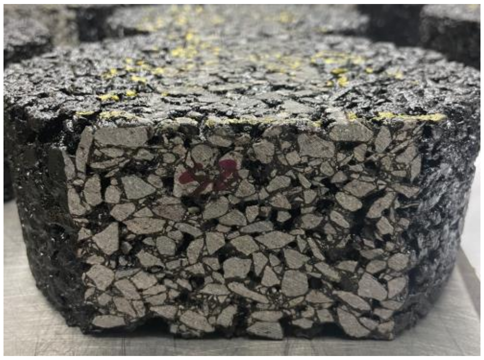

Figure 20. Mustang Q&D Tested Sample under Non-Studded Tire Side View (Condition 1)

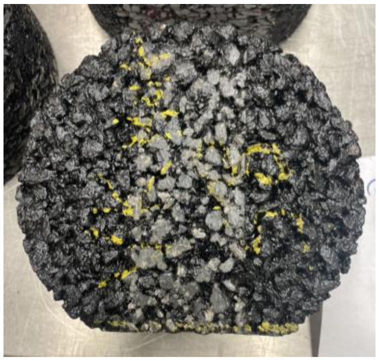

Figure 19. Mustang Q&D Tested Sample under Studded Tire Top View (Condition 1)

Figure 22. Lockwood Tested Sample under Studded Tire Side View (Condition 1)

Figure 21. Lockwood Tested Sample under Studded Tire Top View (Condition 1)

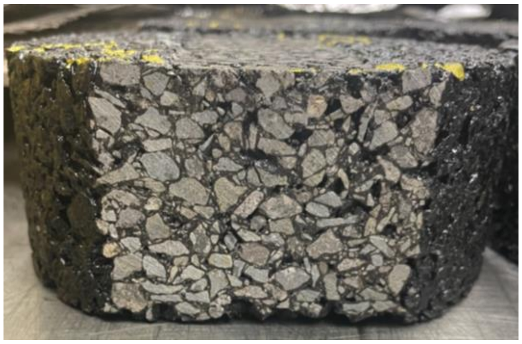

Figure 24. Lockwood Tested Sample under Non Studded Tire Side View (Condition 1)

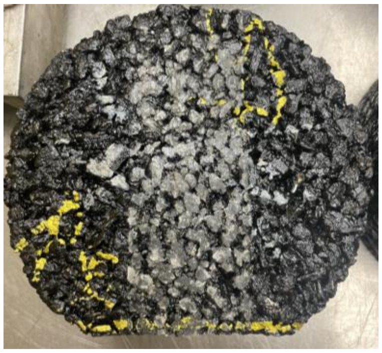

Figure 23. Lockwood Tested Sample under Non Studded Tire Top View (Condition 1)

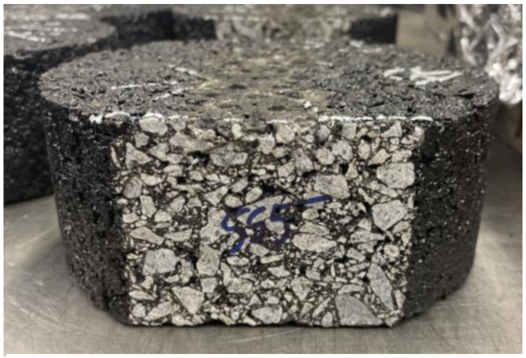

Figure 26. Spanish Springs Tested Sample under Studded Tire Side View (Condition 1)

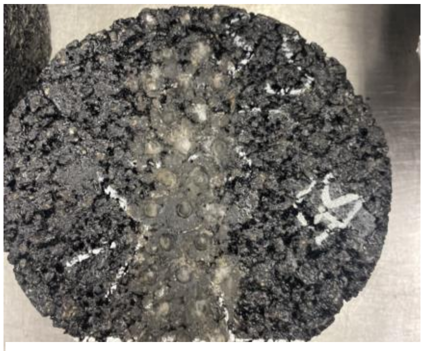

Figure 25. Spanish Springs Tested Sample under Studded Tire Top View (Condition1)

Figure 28. Spanish Springs Tested Sample under Non Studded Tire Side View (Condition 1)

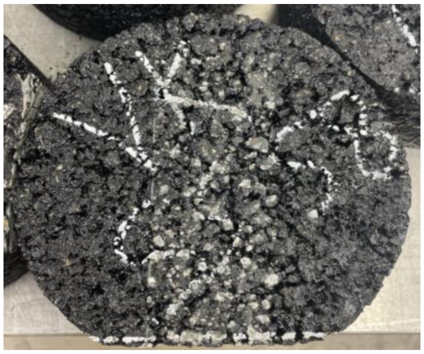

Figure 27. Spanish Springs Tested Sample under Non Studded Tire Top View (Condition 1)

Figure 30. Mustang Western Nevada Tested Sample under Studded Tire Side View (Condition 1)

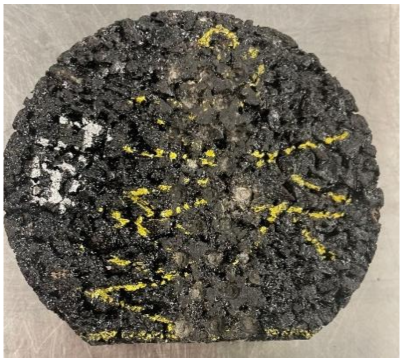

Figure 29. Mustang Western Nevada Tested Sample under Studded Tire Top View (Condition 1)

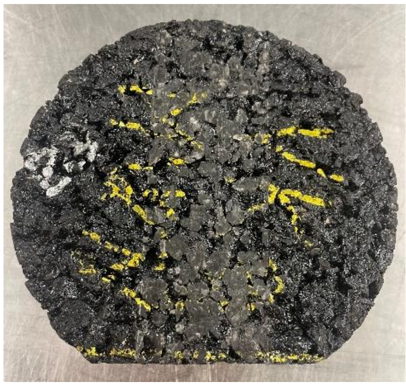

Figure 31. Mustang Western Nevada Tested Sample under Non Studded Tire Top View (Condition 1)

Figure 32. Mustang Western Nevada Tested Sample under Non Studded Tire Side View (Condition 1)

Figure 33. Brunswick Tested Sample under Studded Tire Top View (Condition 1)

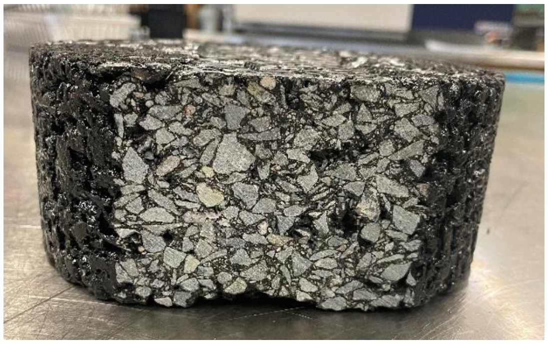

Figure 34. Brunswick Tested Sample under Studded Tire Side View (Condition 1)

Figure 36. Brunswick Tested Sample under Studded Tire Side View (Condition 1)

Figure 35. Brunswick Tested Sample under Studded Tire Top View (Condition 1)

Table 16. Hamburg Wheel Track Test Results (Condition 1)

Source	Mustang Q&D	Lockwood	Brunswick	Mustang Western Nevada	Spanish Springs
Test Temperature (°C)	23				
Condition	Dry				
Specimen Structure	Open Graded				
Rut Depth After 20000 Passes (mm) (Studded Tire)	4.6	4.4	4.1	3.9	4.2
Rut Depth After 20000 Passes (mm) (Non-Studded Tire)	1.9	2.2	1.6	1.4	1.6
Air Voids (%)	15	16	14	13	8
Bitumen Ratio (%)	6.5	7.1	6.8	6.5	6.7
Percent Effective Binder (%)	5.1	5.2	5.0	4.9	5.8

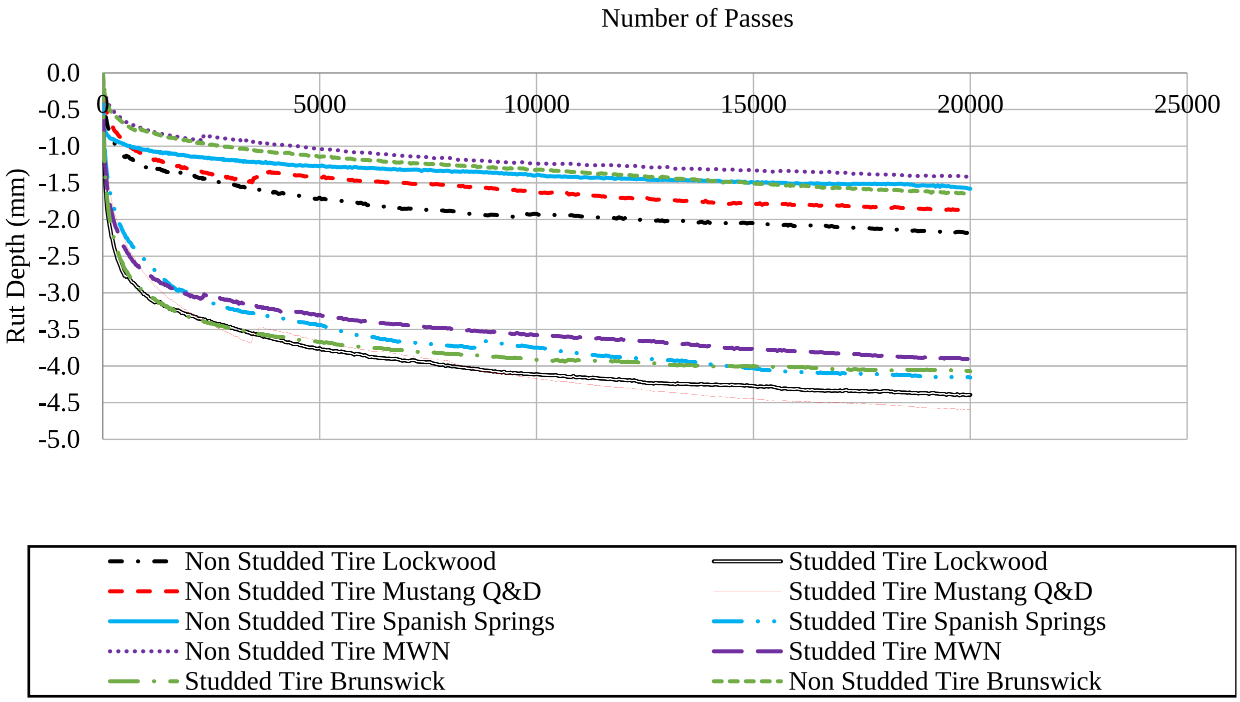

Figure 37. Hamburg Wheel Track Test Results (Condition 1)

b. Condition 2

Condition 1 did not generate significant damage to the asphalt concrete mixtures tested and the comparison between the performance of the different sources was not possible, therefore condition 2 was introduced. In this test, the non-studded tire resulted in higher rut depths compared to the non-studded tire. In addition, the effect of water was evident as stripping was observed for the Spanish Springs materials only. Also, Lockwood samples reached the rut depth threshold set for this test (12.5 mm) after approximately 10000 cycles. Figures 39 through 53 show the condition of samples after test with both studded and non-studded wheels. Due to time restrictions, the Brunswick Material was not tested under Condition 2. Table 17 shows the summary of HWTT results at condition 2. Figure 54 illustrates the rut depth versus the number of passes curves.

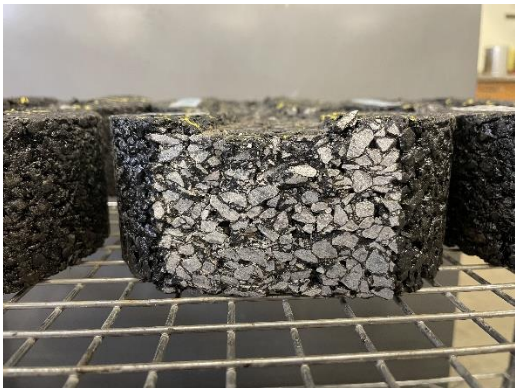

Figure 39. Mustang Q&D Tested Sample under Studded Tire Side View (Condition 2)

Figure 38. Mustang Q&D Tested Sample under Studded Tire Top View (Condition 2)

Figure 41. Mustang Q&D Tested Sample under Non Studded Tire Side View (Condition 2)

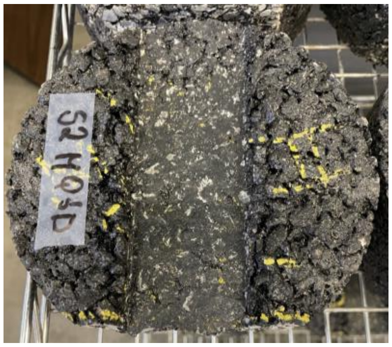

Figure 40. Mustang Q&D Tested Sample under Non Studded Tire Top View (Condition 2)

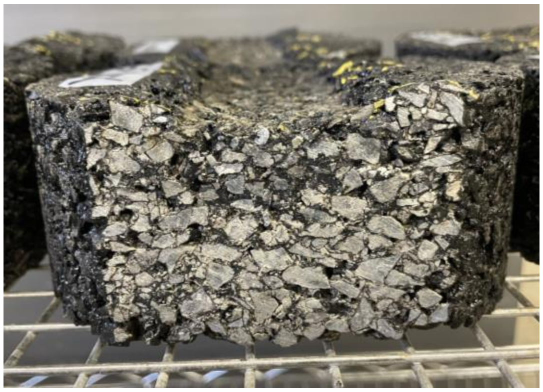

Figure 42. Lockwood Tested Sample under Studded Tire Side View (Condition 2)

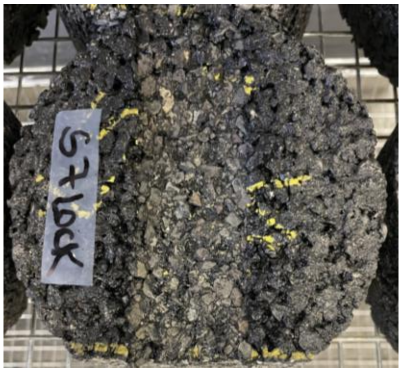

Figure 43. Lockwood Tested Sample under Studded Tire Top View (Condition 2)

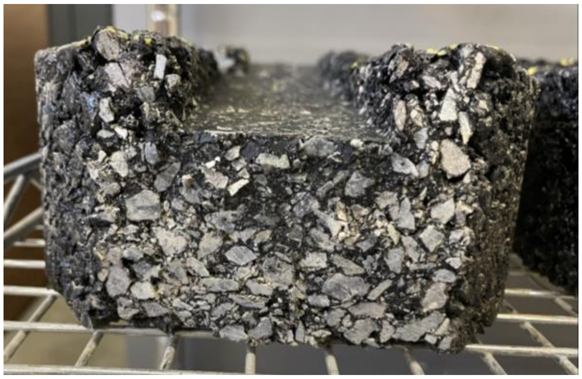

Figure 44. Lockwood Tested Sample under Non Studded Tire Side View (Condition 2)

Figure 45. Lockwood Tested Sample under Non Studded Tire Top View (Condition 2)

Figure 46. Spanish Springs Tested Sample under Non Studded Tire Side View (Condition 2)

Figure 47. Spanish Springs Tested Sample under Non Studded Tire Side View (Condition 2)

Figure 48. Spanish Springs Tested Sample under Non Studded Tire Side View (Condition 2)

Figure 49. Spanish Springs Tested Sample under Non Studded Tire Side View (Condition 2)

Figure 50. Mustang Western Nevada Tested Sample under Studded Tire Side View (Condition 2)

Figure 51. Mustang Western Nevada Tested Sample under Studded Tire Side View (Condition 2)

Figure 52. Mustang Western Nevada Tested Sample under Non Studded Tire Side View (Condition 2)

Figure 53. Mustang Western Nevada Tested Sample under Non Studded Tire Top View (Condition 2)

Table 17. Hamburg Wheel Track Test Results (Condition 2)

Source	Mustang Q&D	Lockwood	Mustang Western Nevada	Spanish Springs
Test Temperature (°C)	50			
Condition	Wet			
Specimen Structure	Open Graded			
Rut Depth After 20000 Passes (Studded Tire)	7.0	6.9	4.7	5.8
Rut Depth After 20000 Passes (Non-Studded Tire)	10.0	11.6	7.6	9.4
Air Voids (%)	17	16	13	8
Bitumen Ratio (%)	6.5	7.1	6.5	6.7
Stripping Inflection Point (Number of Passes)	N/A	N/A	N/A	12952
Percent Binder Effective (%)	5.1	5.2	4.9	5.8

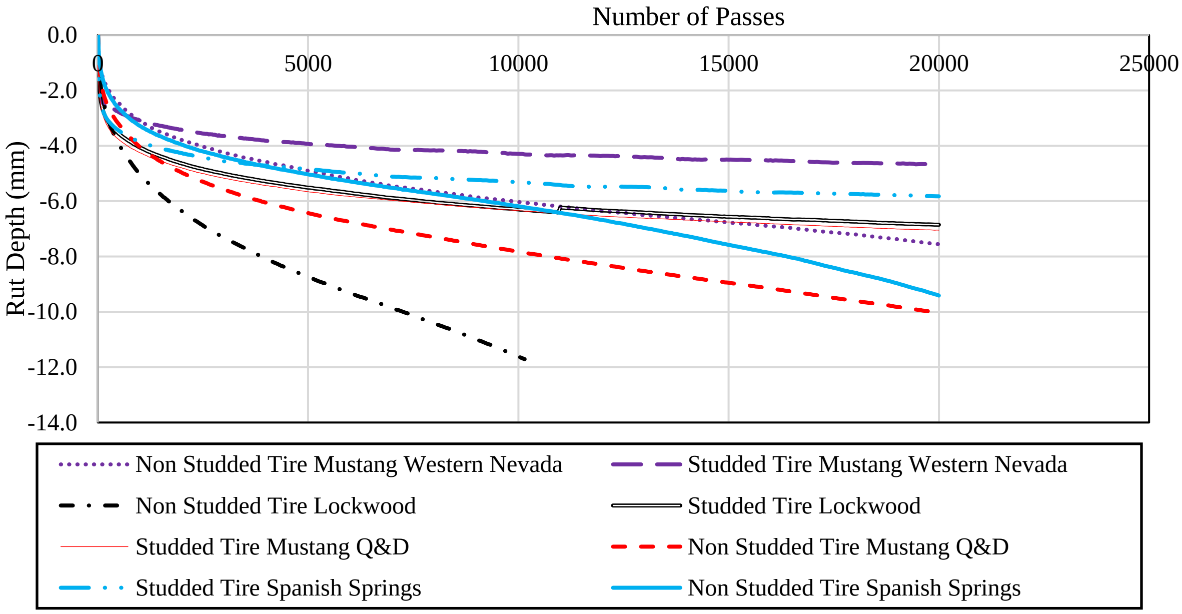

Figure 54. Hamburg Wheel Track Test Results (Condition 2)

c. Condition 3

The actual pavement structure existing in the field consists of a dense graded material covered by a thin OGFC on top. To have a better representation of the field specimens, Condition 3 was introduced. Figures 55 through Figure 69 show the samples created in the lab. The samples were tested at intermediate temperature and dry condition to compare the results with condition 1 results. The non-studded and studded tires both resulted in lower rut depth in condition 3 compared to condition 1, except for the Mustang Western Nevada Source. This was anticipated as the air void level in the samples tested at condition 3 is lower than those tested at condition 1 as the dense graded portion was introduced in samples tested at condition 3. It should be mentioned that the rut depths observed at condition 1 and condition 3 are not statistically different. This was observed based on the analysis of variance table (ANOVA), where a p-value of 0.18 was obtained for studded tire results and 0.052 was obtained for non-studded tire results. This indicates that at intermediate temperature and dry conditions, open graded samples generated statistically the same performance as the open graded on top of the dense graded samples. Due to time restrictions, the Brunswick Material was not tested at Condition 3.

Figure 55. Mustang Q&D Tested Sample under Studded Tire Top View (Condition 3)

Figure 56. Mustang Q&D Tested Sample under Studded Tire Top View (Condition 3)

Figure 58. Mustang Q&D Tested Sample under Non-Studded Tire Side View (Condition 3)

Figure 57. Mustang Q&D Tested Sample under Non Studded Tire Top View (Condition 3)

Figure 59. Lockwood Tested Sample under Studded Tire Side View (Condition 3)

Figure 60. Lockwood Tested Sample under Studded Tire Top View (Condition 3)

Figure 61. Lockwood Tested Sample under Non Studded Tire Side View (Condition 3)

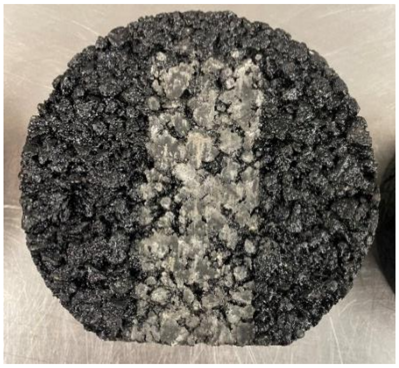

Figure 62. Lockwood Tested Sample under Non Studded Tire Top View (Condition 3)

Figure 64. Spanish Springs Tested Sample under Studded Tire Side View (Condition 3)

Figure 63. Spanish Springs Tested Sample under Studded Tire Top View (Condition 3)

Figure 66. Spanish Springs Tested Sample under Non Studded Tire Side View (Condition 3)

Figure 65. Spanish Springs Tested Sample under Non Studded Tire Side Top (Condition 3)

Figure 67. Mustang Western Nevada Tested Sample under Studded Tire Side View (Condition 3)

Figure 68. Mustang Western Nevada Tested Sample under Studded Tire Side View (Condition 3)

Figure 70. Mustang Western Nevada Tested Sample under Non Studded Tire Side View (Condition 3)

Figure 69. Mustang Western Nevada Tested Sample under Studded Tire Top View (Condition 3)

Table 18. Hamburg Wheel Track Test Results (Condition 3)

Source	Mustang Q&D	Lockwood	Mustang Western Nevada	Spanish Springs
Test Temperature (°C)	23			
Condition	Dry			
Specimen Structure	Open Graded + Dense Graded			
Rut Depth After 20000 Passes (Studded Tire)	3.9	4.0	4.2	4.0
Rut Depth After 20000 Passes (Non-Studded Tire)	1.2	1.6	1.2	0.9
Air Voids of Open Graded Lift (%)	15	16	13	8
Air Voids of Dense Graded Lift (%)	7 ± 1			
Bitumen Ratio (%)	6.5	7.1	6.5	6.7
Percent Binder Effective (%)	5.1	5.2	4.9	5.8

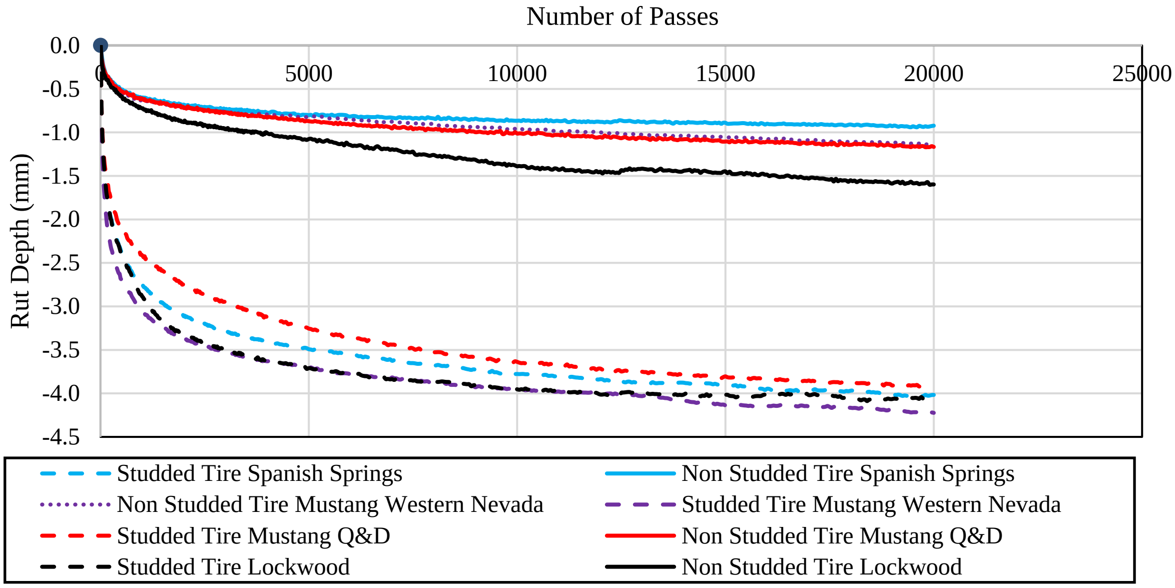

Figure 71. Hamburg Wheel Track Test Results (Condition 3)

d. Laser Texture Measurement

The Mean Profile Depth (MPD) of the surface of X sample types was determined and shown in Table 10. The observed MPD was similar for all the sources although the gradations varied among the sources. The Spanish Springs source had the smoothest texture, which was expected as it has the finest gradation and the lowest air void level compared to the other aggregate sources. The Lockwood source had the roughest texture, which was also expected as it has the coarsest gradation, and the highest air voids level compared to the other aggregate sources. The change in the MPD before and after the HWTT was determined in percent and is shown in Table 11. The MPD decreased for all the samples after performing the test which was anticipated. Only the Lockwood source in Condition 3 was an exception where the MPD increased after performing the test. The decrease in MPD after the test is because crushed aggregates during the test are filling the voids in the open-graded samples making the samples surfaces denser. It should be noted that the measurements taken on the samples after running the HWTT at condition 2 cannot be considered reliable. This is because the samples showed very high shear deformation and it was not possible to fit these samples in the testing apparatus.

Table 19. Mean Profile Depth

Source	Mean Profile Depth (inch)
Spanish Springs	0.042
Mustang Western Nevada	0.052
Lockwood	0.064
Mustang Q&D	0.056

Table 20. Mean Profile Depth Results before and after The Hamburg Wheel Track Test

Source	Tire Condition	Condition 1	Condition 2	Condition 3
Mustang Q&D	Studded	31.3%	N/A	14.5%
	Non Studded	41.4%		11.4%
Mustang Western Nevada	Studded	25.5%		18.5%
	Non Studded	7.6%		22.6%
Lockwood	Studded	21.2%		-23.3% [*]
	Non Studded	31.7%		4.8%
Spanish Springs	Studded	17.4%		9.1%
	Non Studded	31.6%		17.8%

[*] The negative value indicates an increase in the mean profile depth after the test has been performed

3. Prall Test (ATM 420) (ATM, 2023)

The criteria used to evaluate the wear resistance was based on an AKDOT test criteria as shown in Table 21 (Brunette, 2003). The Prall test results are shown in Table 22 and 23 for both LMLC and FMFC samples, respectively. For LMLC samples, Lockwood showed the worst performance while the Mustang Q&D showed the best performance. The Spanish Springs and Mustang Western Nevada Source materials showed satisfactory wear resistance. It is worth noting that although Mustang Western Nevada materials had the same gradation and same bitumen ratio as Mustang Q&D source, the Mustang Western Nevada materials showed worse performance compared to the Mustang Q&D source. Another interesting observation is that Mustang Western Nevada samples had a lower air void level than the Mustang Q&D source. Despite this, Mustang Q&D source still exhibited higher wear resistance than the Mustang Western Nevada. For the FMFC samples a different trend was observed. Lockwood cores were exhibiting the best performance among the other sources, while Mustang Q&D and Spanish Springs showed lower resistance. Figure 72 through Figure 78 show the tested samples.

Table 21. Wear Resistance Criteria (Brunette,2003)

Prall-loss (cm^3)	Wear Resistance
<20	Very Good
20-29	Good
30-39	Satisfactory
40-50	Less Satisfactory
>50	Poor

Table 22. Prall Test Results for LMLC

Source	Air Voids (%)	Bitumen Ratio (%)	Abrasion Value (cm^3)	Wear Resistance
Spanish Springs	11.8	6.7	32.5	Satisfactory
Mustang Western Nevada	13.9	6.5	32.8	Satisfactory
Lockwood	16.8	7.1	44.9	Less Satisfactory
Mustang Q&D	16.1	6.5	27.3	Good

Table 23. Prall Test Results for FMFC

Source	Air Voids (%)	Bitumen Ratio (%)	Abrasion Value (cm^3)	Wear Resistance
Mustang Q&D	17.0	7.0	56.2	Poor
Spanish Springs	8.0	7.0	64.8	Poor
Lockwood	10.0	7.0	34.7	Satisfactory

Figure 72. Lockwood LMLC Tested Samples

Figure 73. Mustang Q&D LMLC Tested Samples

Figure 75. Mustang Western Nevada LMLC Tested Samples

Figure 74. Spanish Springs LMLC Tested Samples

Figure 76. Lockwood FMFC Tested Samples

Figure 77. Mustang Q&D FMFC Tested Samples

Figure 78. Spanish Springs FMFC Tested Samples

Chapter 6: Statistical Analysis

Summary of Data

A summary of all the test results is shown in Table 24. The Brunswick Material was not included in the statistical analysis as the tests for this source were not all completed at the time of this writing. It is important to note that the available data is limited, and for a rigorous statistical analysis a broader data set would be necessary. Nevertheless, this is the extent of the information currently available.

Using RStudio, a statistical analysis software, analyses were performed. The Pearson correlation was obtained between all the parameters, and several were identified as being significantly correlated. The Pearson correlation indicates the strength and direction of the linear relationship between two continuous variables. The coefficient of determination R^2 was also determined as the squared of the Pearson correlation. This is true since single linear regression analysis is performed. A significance level of 0.05 was used in this study.

The only parameters that showed significance correlation between eachother were the: Prall abrasion value and the fine aggregate durability. rut depth of studded tire at condition 2 and the rut depth of the non studded tire at condition 1; and rut depth of the non studded tire at condition 2 and the rut depth of studded tire at condition 1. These parameters are plotted in Figures 79 through 81. The p-value obtained for each correlation test was lower than 0.05 therefore, the correlation is considered significant.

Table 24 . Summary of Test Data

Source	Mustang Q&D	Spanish Springs	Mustang Western Nevada	Lockwood
Air Voids (%)	17.6	11.8	13.9	16.8
Bitumen Ratio (%)	6.5	6.7	6.5	7.1
Binder Effective (%)	5.1	5.8	4.9	5.2
Abrasion Value (cm^3)	27.3	32.5	32.8	44.9
Rut Depth (Non Studded) *[Condition 1]* (mm)	1.9	1.6	1.4	2.2
Rut Depth (Studded) *[Condition 1]* (mm)	4.6	4.2	3.9	4.4
Rut Depth (Non Studded) *[Condition 2]* (mm)	7	5.8	4.7	6.9
Rut Depth (Studded) *[Condition 2]* (mm)	10	9.4	7.6	11.6
Rut Depth (Non Studded) *[Condition 3]* (mm)	1.2	0.9	1.2	1.6
Rut Depth (Studded) *[Condition 3]* (mm)	3.9	4.0	4.2	4.0
Cantabro Loss (%)	1.3	0.9	1.9	0.6
LA Abrasion (%)	14	22	21	19
Sand Equivalent (%)	85	84	71	73
Fine Aggregate Durability (%)	95	87	85	75

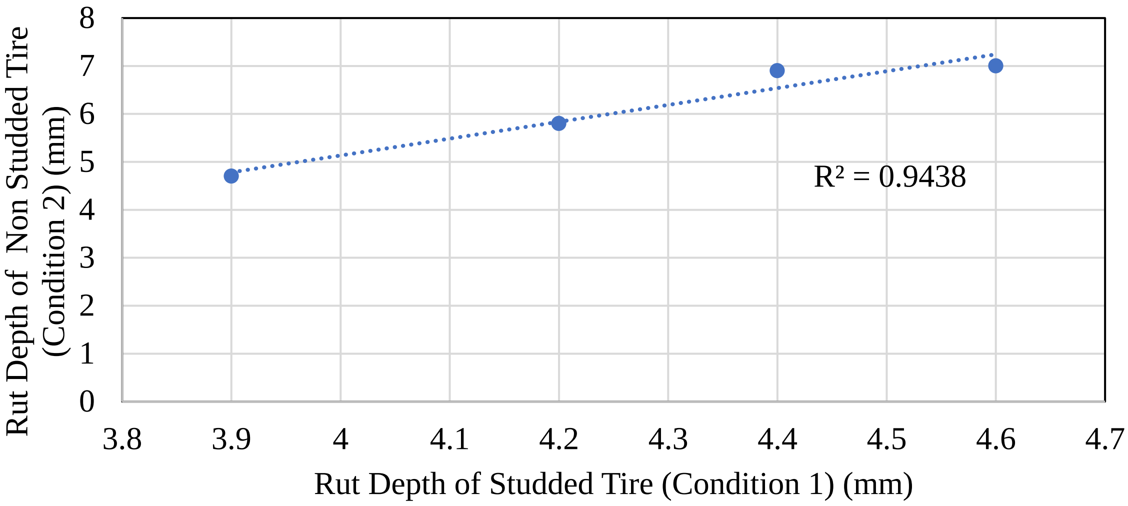

Figure 79. Rut Depth of Non Studded Tire at Condition 2 versus Rut Depth of Studded Tire at Condition 1

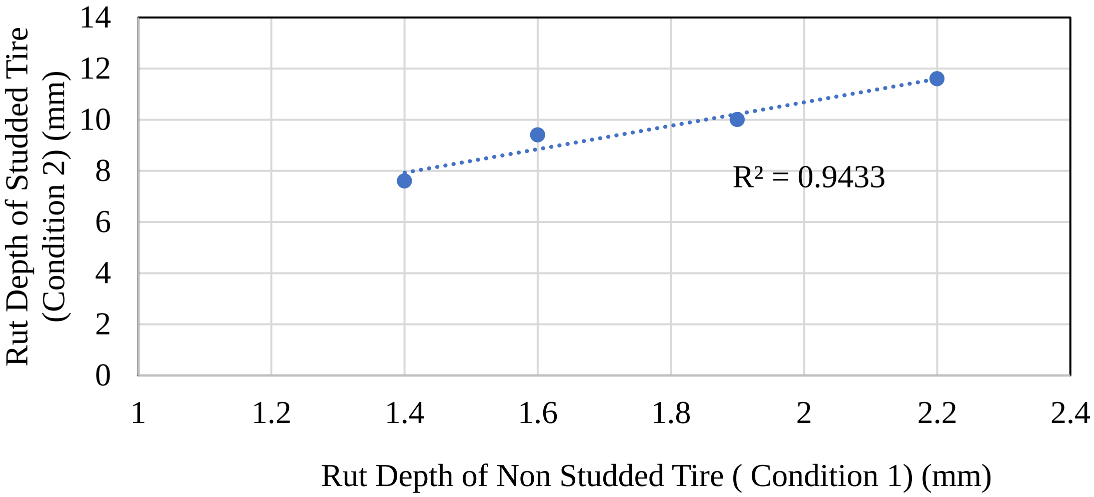

Figure 80. Rut Depth of Studded Tire at Condition 2 versus Rut Depth of Non Studded Tire at Condition 1

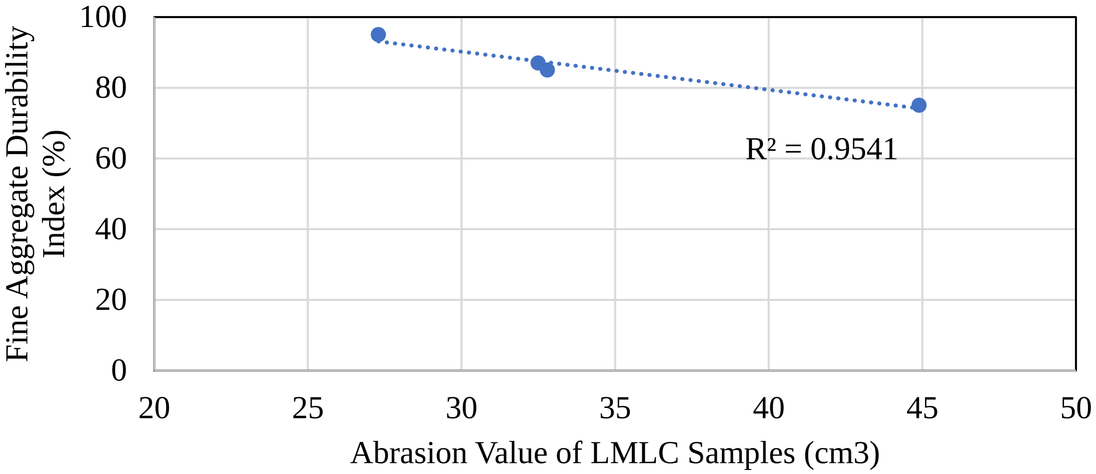

Figure 81. Fine Aggregate Durability Versus Abrasion Value of LMLC

Chapter 7: Findings and Recommendations

Based on the statistical analysis, it could be concluded that the HWTT performed under the three conditions described in this report, were not correlated to the Prall Abrasion values. Therefore, the HWTT at the conditions considered in this thesis is not considered a reliable test to simulate studded tire damage. It is recommended to run the HWTT at low temperature to better simulate winter field conditions as studded tires are usually used only in the winter.

Interesting correlations were found between different HWTT testing conditions. A positive relationship was observed between rut depth generated by the studded tire at condition 1 and the non-studded tire at condition 2. Moreover, a significant positive correlation was found between the rut depth generated by the non-studded tire at condition 1 and the studded tire at condition 2.

For Condition 3, being the most representative to the scenario encountered in the field, it is recommended to test the open-graded over dense-graded structures at low temperature with the purpose of creating enough damage to the samples to make it possible to better compare differences between sources. Condition 2 of the test should not be recommended to evaluate the studded tire resistance of different sources as the effect of water comes into play and the high temperature affects the results, while the studded tires are used in the winter at low temperatures.

This study verified findings obtained in previous research where the Los Angeles Abrasion test showed no significant relationship with studded tire resistance, as it showed no correlation with the Prall Test (Johnson et. al,2000). This finding also applied to the

Cantabro test as no significant link was found between this test and the Prall test.

The only test that showed a significant correlation with studded tire resistance was the fine aggregate durability test. Therefore, it is recommended to consider this aggregate test in future studies for evaluating studded tire resistance.

It is recommended that the different sources be compared in terms of studded tire resistance to have similar properties while having only one variable, which could be either air void level, gradation, or bitumen ratio. Otherwise, it will not be possible to capture which of these factors is the most influential on the OGFC behavior.

Finally, the second phase of this project should consist of testing field cores using HWTT at suitable testing conditions. This testing should include the Brunswick source also.

Chapter 8: References

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