AMERICAN UNIVERSITY OF BEIRUT

# INVESTIGATING THE RUTTING AND MOISTURE SUSCEPTIBILITY OF ASPHALT MIXTURES USING ACCELERATED PAVEMENT TESTING AND ESTABLISHING PERFORMANCE BASED PAY FACTORS

by
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# ABSTRACT
# OF THE THESIS OF

Ali Jamal Faisal for Master of Engineering
Major: Materials and Pavement Engineering

Title: Investigating the Rutting and Moisture Susceptibility of Asphalt Mixtures Using Accelerated Pavement Testing and Establishing Performance Based Pay Factors

The objective of this research is to assemble and instrument an accelerated pavement tester (APT) that can reliably be used in asphalt mixtures evaluation. Several applications were conducted on the APT. The APT used in this study was designed, assembled, and instrumented to allow simultaneous accelerated testing of different asphalt mixtures, in both dry and wet conditions, at different load amplitudes and temperatures. The first two applications included asphalt mixtures with deviations in their binder content and air voids based on the standard specifications of transportation agencies and department of transportation for different states. Then, pay factors that are based on performance metrics were established according to the relative performance of each tested mixture. The purpose of the third application was to investigate the rutting potential and moisture susceptibility of different asphalt mixtures subjected to various loading conditions using an APT. The experimental plan was divided into two stages. Stage one included testing six different asphalt mixtures under dry conditions. This stage aimed at assessing the effect of recycled concrete aggregates (RCA) as a percentage replacement of the coarse aggregates, RCA as a mineral filler, and hydrated lime filler, while incorporating unmodified as well as SBS-modified binders. The second stage included testing the same asphalt mixture variations but under wet conditions. During testing, the rut depth at the center of each sample was recorded at regular intervals to construct the permanent deformation curves as a function of the number of load cycles. The established performance-based pay factors were reasonable and comparable with those set under penalties by DOTs. However there were some limitations that are discussed in the study. Moreover, results of the third application indicated that including hydrated lime filler into mixtures with RCA aggregates could lessen the rutting potential exacerbated by moisture damage. However, excessive bleeding was observed in mixes incorporating both SBS-modified binder and hydrated lime. In addition, asphalt mixtures incorporating RCA aggregates exhibited higher moisture damage, while those with RCA mineral filler had similar performance to mixtures with limestone filler in terms of rutting and moisture susceptibility.

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# ABBREVIATIONS

| | |
|---|---|
| AUB | American University of Beirut |
| AASHTO | American Association of State Highway and Transportation Officials |
| ASTM | American Society for Testing and Materials |
| RCA | Recycled Concrete Aggregate |
| APA | Asphalt Pavement Analyzer |
| HWTT | Hamburg Wheel Tracking Tester |
| MMLS3 | One third scale Model Mobile Load Simulator |
| DSR | Dynamic Shear Rheometer |
| SBS | Styrene-Butadiene-Styrene |
| PG | Performance Grade |
| NCHRP | National Cooperative Highway Research Program |
| APT | Accelerated Pavement Tester |
| DOT | Department of Transportation |
| FHWA | Federal Highway Agency |
| RTFO | Rolling Thin Film Oven |
| BBR | Bending Beam Rheometer |
| AMPT | Asphalt Mix Performance Tester |
| ALF | Australian Loading Facility |
| HVS | Heavy Vehicle Simulator |
| ATLAS | Accelerated Transportation Loading Assembly |
| HMA | Hot Mix Asphalt |
| DM | Dynamic Modulus |
| RAP | Reclaimed Asphalt Concrete |

# CHAPTER 1

# INTRODUCTION

Asphalt binder, also referred to as bitumen, was first introduced in the early 13$^{th}$ century (Vaaorg, 2020). The substance naturally occurs as residue that forms on top of surfaces under petroleum deposits. The sticky material can also be produced from the residue that remains after the distillation of petroleum to extract fuel/lubricants. It was first used as an adhesive material and sealants and then incorporated into asphalt mixtures. The importance of asphalt concrete rose in World War II where technological innovations in asphalt technology were enhanced, driven by the military need for roads that can withstand heavy aircraft. Today, over 90% of roads built in the United States are made of asphalt concrete (Buncher, 2018). Asphalt concrete is made up of asphalt binder, a viscous and durable binding agent, mixed with coarse and fine aggregates. Given the cost effectiveness, long-term design life, and sustainable prospects of asphalt pavements, governments started the flow of investments to improve the design and performance of asphalt-paved roads. As such, agencies of the likes of American Association of State Highway and Transportation Officials (AASHTO) and Federal Highway Administration (FHWA) put efforts in advancing the characterization and performance of asphalt concrete.

## 1.1. Early Empirical Design Methods

The first empirical test to evaluate bituminous materials was the California Bearing Ratio (CBR). It is developed by the United States California Division of

Highway in 1920, which indicates the penetration resistance ratio between the test material and a standardized granular layer.

The first milestone in terms of setting a design protocol was introduced by AASHTO's road tests conducted within four years from 1958 till 1962 which resulted in the AASHTO Design Guide in 1993. (Sun, 2016) The guide developed the concept of Present Serviceability Index (PSI), a numerical rating out of 5, and presented a method to convert traffic into Equivalent Single Axle Load (ESAL), which both correlated to the structural integrity of asphalt pavements and the terminal serviceability index.

### 1.2. Recent Developments in Pavement Engineering Design Methods

Transitioning from an empirical-based design, mechanistic-based pavement design and analysis emerged in the 1960s. Several protocols were developed, most prominently, the Shell design method, the Asphalt Institute method, the French design method and lastly, FHWA's mechanistic-empirical method which integrates the pavement response under loading and relates it with pavement performance. After $150 million were invested by the US congress for the Strategic Highway Research Program (SHRP) in 1987, performance-based design methods were developed. Superior Performing Asphalt Pavements (SuperPave) studies the physical and chemical properties of asphalt binder and sets a goal to design pavements that possess an acceptable rut resistance, fatigue resistance and low temperature cracking resistance. (Sun, 2016)

Currently, SuperPave has become a standard guideline adopted in innovative pavement research as well as in construction work. In addition to providing a performance-based method, it also sets performance-based specifications and test equipment. These test equipment cover all processes for asphalt experimental work: aggregate testing equipment including the Los Angeles abrasion machine, Superpave oven, water bath, aggregate gradation sieve shaker and sieves, to name a few.

Hot Mix Asphalt (HMA) Superpave mix test equipment include but are not limited to : (1) Marshal stability and indirect tensile test, (2) Hamburg wheel tracker, and (3) Asphalt mix performance tester (AMPT). Equipment for bitumen testing, for example, include: (1) dynamic shear rheometer (DSR), (2) bending beam rheometer, and (3) rolling thin film oven (RTFO).

In performance-based testing, the Hamburg wheel tracker is one prototype of an accelerated pavement tester (APT). There are three types of APT: (1) Full-scale APT, (2) Scaled-down APT and (3) rut testers. Full scale accelerated pavement testing is defined as the controlled application of a prototype wheel loading, at or above the appropriate legal load limit, to a prototype or actual, layered, structural pavement system to determine pavement response and performance under a controlled, accelerated, accumulation of damage in a compressed time (Metcalf, 1996). Even though full-scale accelerated pavement testing provides a testing setting that is closely related to actual trafficking, it can be excessively expensive to prepare, operate and maintain. In the same context, there comes a need to test asphalt pavements under an accelerated pavement tester in a compact fashion, while also holding the functionality and effectiveness of the full-scaled devices; scaled-down APT and rut testers serve this purpose. The objective of this thesis is to instrument and prepare an accelerated pavement tester that can evaluate different asphalt mixes' rutting performance in a cost-effective and reliable manner and establish pay factors based on performance metrics.

Additionally, using the APT, a moisture susceptibility and rutting potential investigation on different asphalt mixtures are conducted.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. Test-Tracks

In the largest scale, test tracks are road sections that allow the construction and instrumentation of asphalt pavements that are built specially for the simulation of actual trafficking of diverse types of vehicles. The advantage of test tracks over accelerated pavement testers is that they provide genuine weather conditions that the asphalt pavement structure is subjected to, along with trafficking using typical vehicles that are used by drivers; thus, leading to organic testing conditions that simulate pavement distresses close to those of in-service roads.

The National Center for Asphalt Technology (NCAT), partnered with Minnesota department of transportation's MnRoad facility, offers pavement sections that are instrumented for different purposes. Moreover, different performance experimentations are conducted periodically, such as rut depths, macrotextures, high speed structural response data and pavement surface characterization; over prolonged periods of time.

Moreover, the Larson institute at the University of Pennsylvania includes an oval test track that allows and accommodates a wide range of research in asphalt pavements. Similarly, funded by the FHWA, WesTrack gave researchers and engineers the opportunity to investigate several asphalt mix designs through different sections of the 2.9 $km$ oval track, and provide early verification of performance-prediction models.

## 2.2. Early Accelerated Pavement Testers

Accelerated pavement testers were built in various forms and date back to 1913. For example, “the paving determinator 1909” by (Hines,1996) in Detroit

Physical Laboratory Road Machine was built in 1911, Indonesian Test Circuit in the late 1920s. Also, AASHTO Road Tests commenced accelerated pavement testing in 1958 in the United States and marked the first modern pavement testing facility as opposed to the trial experimentation in the field that is subjected to actual trafficking. Also, full-scale circular tracks were constructed at the University of Illinois (Barenberg, 1967), Indiana (Speer,1960), and Washington (Ekse and LaCross, 1957). In recent research, there are 37 full-scale APT facilities around the world having three types of test tracks: (1) circular test tracks, (2) linear test tracks, and (3) shaped test tracks (Sun, 2016).

## 2.3. Scaled-Down Accelerated Pavement Testers

Scaled-down APT are a sized down versions of full-scale testing tracks that are compact. They consist of a wheel, either rubber or steel, that alternates back and forth over asphalt specimens that are subjected to a specific load and tested at a target temperature in a dry state or conditioned in a water bath. Currently, prominent scaled-down accelerated pavement testers are the Hamburg wheel tracking tester, asphalt pavement analyzer, and one third scale mobile load simulator; they are widely used in research evaluating asphalt mixtures’ performance for rutting and moisture susceptibility.

### *2.3.1. Hamburg Wheel Tracking Test*

The Hamburg Wheel Tracking Test (HWTT), shown in figure 1, was developed by Helmut-Wind Incorporated of Hamburg, Germany. It is utilized as a specification requirement for some of the most traveled roadways in Germany to evaluate rutting and stripping.

Tests within the HWTT are done either on a slab that is $260\ mm$ wide, $320\ mm$ long, and typically $40\ mm$ high ($10.2\ in\ x\ 12.6\ in\ x\ 1.6\ in$) or sawed and cut cylindrical shape specimens. These slabs are normally compacted to $7 \pm 1$ percent air voids using a linear kneading compactor. Testing using the HWTT is conducted with the samples submerged in a water bath at temperatures ranging from $25°C\ to\ 70°C$, however $50°C$ is the most common temperature. Loading of samples in the HWTT is accomplished by applying a $158\ lb$ force onto a $47\ mm$ wide steel wheel; the steel wheel is then reciprocated over the specimens at a speed of $340\ mm$ per second. Test samples are trafficked for $20{,}000$ passes or until reaching a failure criterion of $20\ mm$ deformation

Figure 1: Hamburg wheel tracking tester (Geo Lab Nemo, 2017)

There are numerous studies that incorporated the HWTT in its experimental plan to better characterize asphalt performance. A study by (Ling et al,2020) investigated the rutting characteristic of two HMA overlays, asphalt concrete (AC) and stone mastic asphalt (SMA) under high tire pressure.

Investigations were conducted on 38 cored samples in the lab and were used for the density test, HWTT, and uniaxial penetration test. It was reported that the rut depths for the HMA layer were 40.8% higher than the SMA.

Another study carried by (Walubita et al, 2012) compared three rutting tests, HWTT, dynamic modulus, and repeated load permanent deformation (RLPD), of HMA in the lab to actual field performance. The DM test results were intricately connected to the results of the RLPD and the HWTT. The latter was recommended as the most suitable test for HMA mix-design routinely but lacks in determining material properties. (Walubita et al, 2019) had another similar study conducted in 2019 that confirmed that the HWTT was the most convenient with regard to repeatability and simplicity in predicting rutting performance similar to field testing

When it comes to addressing the effect of rejuvenators on the performance of HMA having a percentage of RAP, (Lee et al, 2019) used eight mixes in their experiment, while having one as control. Performance testing was done using the HWTT for rutting. Consequently, the inclusion of rejuvenators proved to increase penetration of asphalt binder, while its exclusion increased the stiffness which in return enhanced rutting performance.

In terms of moisture susceptibility, the HWTT usage is prominent where (Shu et al, 2012) evaluated moisture susceptibility of foamed WMA having high RAP percentages. These conditioned specimens were then tested using the HWTT. As such, there was a high correlation between the amount of RAP and moisture resistance, where the increasing amounts of RAP increased moisture resistance.

Similarly, (Wu et al, 2015) investigated the effects of adding RAP and Reclaimed Asphalt Shingles (RAS) on the performance of HMA mixes. In regard to the HWTT, the increasing amount of RAP showed added rutting resistance and moisture-induced damage. Likely, asphalt patching mixtures were investigated by (Dong et al., 2012). Three mixes were used for the pothole patching material, namely HMA mixture, cold dump mix and two cold bag mixes. Then, the patching materials were taken to conduct several laboratory tests, namely adhesiveness and cohesion tests, moisture susceptibility by freezing and thawing, and HWTT to study their rutting performance. The findings in the laboratory testing agreed with the results of the field performance

For thermoplastics, (Yoo & Kim, 2014) studied the use of thermoplastic polymer-coated glass fiber and scrap reinforced HMA mixes. After subjecting both fibrous and conventional mixes to 20,000 cycles on the HWTT, the latter exerted at least three times more rutting than the former. This proves the bridging effect of fiber glass on the mix, and its effectiveness in prolonging pavement life.

2.3.1.1. Shortcomings of the Hamburg Wheel Tracking Tester

Although the HWTT is a valuable test method to evaluate the rutting potential and moisture susceptibility of a wide range of asphalt mixtures, there are some controversies that arise. (Qing & Harvey, 2006) reported that the HWTT may overestimate the rutting of mixes with conventional binder, and underestimate mixes with polymer-modified binder. Additionally, the steel wheels tended to "pick-up" the test specimens.

### *2.3.2. Asphalt Pavement Analyzer (APA)*

The APA consists of a wheel that is loaded onto a pressurized linear hose and tracked back and forth over a testing sample to induce rutting. The test is run until $8000$ cycles are reached, over cylindrical or beam asphalt specimens having an air void percentage of $7\%$. The testing temperature is between $40$ and $64$ degrees Celsius. The pressure used is between $100$ and $250\ PSI$.

Figure 2: Asphalt Pavement Analyzer (AsphaltTesting, 2018)

Integrating the ALF, $\frac{1}{3}$Mobile Load Simulator (MMLS3), and APA, (Huang et al., 2016) carried out a comparative evaluation of pavement performance and compared the response that resulted from the three APTs. Results indicated that the APA effectively measures rutting and can be used to rank mixes' performance in terms of permanent deformation. The authors also concluded that the MMLS3 was the best approach to economically, reliably and effectively measure rutting depth and strain response.

Another study by (Sirin et al., 2006) reported that the laboratory experimentation showed that the APA can evaluate rutting performance that is similar to the field measurement under the HVS.

In the domain of airfields, (Mejias-Santiago et al., 2014) focused on accelerated pavement testing of warm mix asphalt (WMA) designed for airfield pavements. Results of the APA indicated that the stiffness of the pavement sections did not change significantly between HMA and WMA and even between the different technologies used to produce the WMA. Rutting performance was not affected by the structural capacity of the pavement sublayers since the earth pressure measurements did not get altered during trafficking. Due to the lesser stiffness of WMA mixes, the rutting performance of HMA was slightly better since they were exposed to more aging during production; however, both mixes could have the same performance given that short periods of curing are implemented. A similar study was done by (Rushing et al., 2012) to assess the ability of the APA to evaluate the performance of rutting resistance under high tire pressure aircraft at the mix design level. As a result, asphalt mixtures under the APA showed increased rutting depths for mixes with increased natural sands. A 10 mm rut depth before 4000 APA load cycles at 250 psi tire pressure was recommended.

To assess how would rutting deformation under actual trafficking would compare with APA trafficking, (Choubane et al., 2000) tested three pavement sections under field trafficking. The results were correlated with samples tested under the APA. They reported that the APA was adequate in ranking the mixes in the same pattern as the field performance, and the authors suggested adopting 7-8 mm and 8-9 mm at 8000 cycles as a limiting criterion. Additionally, (Song et al., 2018) evaluated three types of mixes: (1) asphalt mixtures having 50% RAP, (2) asphalt mixtures containing rejuvenators, (3) WMA having 50% RAP. Rutting resistance and moisture susceptibility were measured using the Asphalt Pavement Analyzer and Hamburg accelerated wheel tester. Asphalt mixtures having rejuvenators exhibited the highest rutting depths. (Bernier et al., 2012) investigated rutting performance of polymer-modified asphalt mixtures having RAP. The addition of RAP binder to slightly modified mixes decreased substantially the permanent deformation under the APA; however, polymer-modified mixes were less sensitive to additions of RAP, especially at low amounts.

<u>2.3.2.1 Shortcomings of the Asphalt Pavement Analyzer</u>

According to NCHRP report 508, as the diameter of the rubber hose increased, there was an increase in the variability in data. In addition, the APA occasionally did not correlate well with field performance rutting, and it was not possible to predict field rut based on APA measurements.

### *2.3.3. Laboratoire Central des Ponts et Chaussees | LCPC Applications*

The LCPC shown in figure 3 has been used in France for over 20 years to assess rutting in asphalt pavements, and costs $\$85{,}000$ (FHWA, 2017). Two $500\ mm$ long, $180\ mm$ wide and $20 - 100\ mm$ thick HMA slabs are tested simultaneously at $50\ ℃$ with a tire pressure of $87\ PSI$. Several studies indicate that the results of the LCPC are closely related to field performance.


Figure 3: French rut tester (Saliani et al., 2021)

Using the LCPC rut tester, (Sengul et al., 2013) analyzed the performance of SBS polymer modified stone mastic asphalt. Under trafficking using LCPC at 25 Celsius after 50,000 cycles, SBS mixtures had better rutting performance such that the mixes exhibited half the rutting depths against conventional mixes. In earlier research, (Tayfur et al., 2007) evaluated the mechanical properties of control and modified asphalt mixtures. Regardless of the additive type, all modified mixtures had better rutting performance under LCPC due to the effect of modifiers in improving adhesion between aggregates.

LCPC was also used in evaluating permanent deformation for hydrated lime and SBS modified asphalt mixtures, such that (Ozen, 2011) prepared mixes with hydrated lime (2L), SBS polymer, and hydrated lime-SBS. LCPC slabs were produced to test under the machine to acquire rutting values. The highest rutting resistance performance belonged to the hydrated lime-SBS mixture. In addition, the modification of mixes by polymers improved overall rutting performance as well. However, field compaction resulted in higher deformation possibly due to more air void content in field asphalt placement. Moreover, in Turkey, LCPC was used to investigate the rutting of basalt and basalt-limestone aggregate combinations for SMA mixtures by (Iskender, 2013). They reported that decreasing the nominal maximum aggregate size (NMAS) has significance with regards to the rutting resistance and aggregate mineralogy when tested under the LCPC wheel tracker. Additionally, rutting resistance in SMA mixtures with limestone aggregates decreased slightly.

(Baaj et al., 2013) evaluated the behavior of asphalt mixes that contain a combination of RAP and asphalt shingle modifier (ASM). Tests included the LCPC wheel-tracking test following AASHTO T283. Increasing the grade of the bitumen significantly improved low temperature cracking resistance for mixes with 25% RAP and 7% ASM; the same enhancement was witnessed in rutting resistance. Comparably, (Sengoz & Topal, 2004) assessed the rutting performance of asphalt mixes with waste shingles. The properties of mixes with shingles waste were similar to the control mix; however, LCPC results show that shingles also improve rutting resistance.

### *2.3.4. One Third Mobile Load Simulator (MMLS3)*

The MMLS3 is made up of four axles, with wheels having $30\ cm$ diameter each and loads the asphalt samples with a unidirectional loading between $470 - 650\ lb$. Tire pressure is inflated up to $116\ psi$. The asphalt briquettes in the MMLS3 are trafficked for 7200 cycles per hour and placed in aluminum moulds for confinement.

Figure 4 MMLS3 (Palomino, 2007)

Several studies utilized the MMLS3 in various applications in asphalt characterization. (Chehab and Tang, 2011; Lee et al., 2014; Tang et al., 2014) evaluated the use of accelerated pavement testing to evaluate roadway products. Findings indicate that the MMLS3 can successfully rank different geogrid types, evaluate interlayers and pavement markings, along with assessing moisture damage. (Huang et al., 2016) compared the rutting response under different APTs, namely ALF, MMLS3 and APA. They reported that the MMLS3 was superior economically and effectively measured rutting depths and strain responses.  (Twagira and Jenkins, 2012) evaluated different bitumen stabilized materials under wet trafficking for moisture damage, while (Lee et al., 2011) investigated the healing effect of asphalt mixtures using the MMLS3.

Table 1 summarizes the main criteria and specifications that are needed to be met by accelerated pavement testers.

Table 1 Summary of main criteria of explored APTs in literature

| APT | Sample Geometry | Loading and Frequency | Stopping Criteria | Testing Temperature |
|---|---|---|---|---|
| HWTT | Slab or cylindrical shaped | $158\ lb$ | $20\ mm\ or\ 20,000$ cycles | $20\ to\ 70$ ℃ |
| APA | Beam or cylindrical shaped | $250\ lb$ over pressurized hose | $12\ mm\ or\ 8,000$ cycles | $40\ to\ 64$ ℃ |
| LCPC | Slab shaped | $500\ lb$ | $30,000$ cycles | $50\ to\ 60$ ℃ |
| MMLS3 | Slab or briquette shaped | $607\ lb$ | Variable | $-5\ to\ 60$ ℃ |

## 2.4. Studies Utilizing RCA in Asphalt Concrete

Asphalt mixtures heavily rely on the incorporation of natural aggregates; however, in the long-term, this practice is unsustainable. Meanwhile, construction waste has been an environmental concern worldwide. In the U.S, construction activities make up 29% of landfill waste (Yu et al. 2013). Therefore, the depletion of natural aggregate sources along with increasing construction waste proposes essential practices that can utilize construction waste by reusing and recycling them. Recycled concrete aggregates

(RCA) is among the construction and demolition waste materials. RCA is made up of natural coarse and fine aggregates (70%) with cement (30%) coating and typically obtained from crushing old concrete structures. Due to the successful usage of RCA in base and sub-base layers of roads, there has been a growing interest in investigating the usage of RCA in asphalt mixtures (Al-Bayati & Tighe, 2019).

One of the researchers who investigated volumetrics of asphalt mixtures utilizing RCA, (Pourtahmasb & Karim. 2014) incorporated five percentages of fine and coarse RCA ranging from 0% to 80% percent into SMA.

The authors report that in order to lessen the increased absorption of bitumen by RCA, it was recommended to soak the aggregates before using to increase their overall performance by reducing the amount of bitumen absorbed and improve adhesion with other constituents in the mixture. Mixtures with RCA content between 20% and 40% performed satisfactorilyy with respect to typical pavement design standards; however, that was not the case with percentages exceeding 40%.

Similarly at the asphalt mixture level, (Al-Bayati and Tighe, 2019) investigated the usage of coarse recycled concrete aggregates (CRCA) in different proportions and treatment methods and their effect on rutting and stiffness characteristics. The finding of the study revealed that the incorporation of different percentages of RCA had an increased rutting resistance and increased stiffness modulus. Also, the authors found that the type and properties of the used RCA has an effect on the potential rutting improvement of asphalt mixtures. When it comes to proportions, although adding RCA in percentages of 15% and 60% improved rutting resistance compared to the control mix, incorporation of RCA at 30% provided stronger rutting resistance.

A complementary study was done by (Mikhailenko et al. 2020) who studied the effect of adding different fractions of RCA into semi-dense asphalt mixtures. The fractions were divided into coarse aggregates, fine aggregates and filler. The mixtures were tested for volumetrics, indirect tensile strength, water sensitivity, and rutting resistance. In terms of rutting resistance, the addition of fine RCA and especially coarse RCA significantly improved rutting resistance.

For mixes using RCA filler, they performed similar to mixes with virgin filler. Counter performance was reported by (Chen et al. 2011), where they found that the performance of asphalt mixes that use RCA filler have improved moisture resistance.

Evaluating the physical and mechanical properties of RCA, (Tahmoorian & Samali, 2018) conducted several laboratory tests to characterize RCA. Their findings state that RCA meets the requirements of conventional aggregates in mix design; however, compensations in mix design should be implemented due to the higher absorption exhibited by RCA due to cracks and adhering mortar and cement paste. In a later study, (Tahmoorian et al. 2020) reported that even though RCA has a higher water absorption rates, it still meets the volumetric specifications of asphalt mixes, and emphasizes that a ratio of 25% should be utilized. (Dokic et al. 2020) investigated the mineralogical-petrographic and physical-mechanical properties of RCA. Based on their testing, they reported that RCA can substitute a portion of natural aggregates in the applications of rigid and flexible pavements.

In terms of moisture susceptibility, (Kavussi et al. 2018) presoaked RCA with acid and nano-pozzolanic slurry to treat and enhance its properties. Different coarse proportions were incorporated into asphalt mixtures ranging from 0% to 50%. Findings show that RCA under the indirect tensile fatigue test (ITFT) exhibited longer fatigue life and less final strain. However, mixes with RCA showed increased moisture susceptibility that was exacerbated with the increase of RCA percentage.

In contrast to literature and assessing the applicability of RCA incorporation into asphalt mixtures, (Cho et al. 2011) conducted several laboratory tests to investigate the properties of RCA. Their findings include that incorporating fine and coarse RCA into asphalt mixtures lead to the least resistance to rutting.

### 2.5. Studies Utilizing Hydrated Lime in Asphalt Mixtures

Hydrated lime is an organic compound also known as Calcium Hydroxide. It has been widely used in asphalt mixtures experimentation by many researchers over the years (Singh et al. 2021; Isamel and Ahmad 2019; Pasandin 2015) due to it is moisture resistance enhancing properties. Hydrated lime is abundantly available and easily applicable into asphalt mixtures ; however, there has been limited and contradicting research when it comes to its usage. (Singh et al. 2021)

To tackle the issues arising from the usage of RCA, (Singh et al. 2021) investigated the inclusion of hydrated lime filler into RCA incorporated bituminous mixtures. The results show improvements in the Marshall stability, indirect tensile strength (ITS) values, and moisture susceptibility by improving the RCA surface and its affinity towards bitumen. Comparable results were reported by (Ismael & Ahmed, 2019) where they state that asphalt mixtures containing hydrated lime exhibited an improvement in their moisture susceptibility under the ITS test. Combining their work on the volumetric properties, permanent deformation, durability and resilient modulus of hydrated-lime modified asphalt mixtures, (Al-tameemi et al. 2019; Al-tameemi et al. 2016) reported that the addition of hydrated lime improves resilient modulus, rutting resistance, moisture susceptibility and fatigue under a wide range of weather temperatures. Also, the study emphasizes the usage of 2.5% of hydrated lime, as exceeding values would take away from the work of binder content.

Contradicting results were reported by (Pasandin et al. 2015) where they evaluated the effect of hydrated lime on the bond between RCA and asphalt binder. Their main conclusions were that the RCA-asphalt bond was not improved with the addition of hydrated lime, contradictory to other research.

Also, the RCA-asphalt binder adhesion was weakened with the increase in the penetration grade of bitumen. The findings of previous mentioned study reflected in the research of (Yilmaz & Yalcin, 2015). Their findings state that hydrated lime as not as effective as other additives such as American gilsonite (AG) in terms of stability, stiffness and wheel tracking tests. (Zaidi et al. 2020) further investigated the role of hydrated lime in bituminous mixtures, where hydrated lime was incorporated into four types of aggregates having different mineralogy. Based on their testing, in terms of retained stiffness and moisture resistance, the improvements or the absence of it varied depending on the aggregate type.

### 2.6. Problem Statement and Motivation

Based on the literature review, it is concluded that the results of the mentioned studies are controversial. The contradiction could be explained by the complexity of asphalt mixtures and the range of factors that affect their performance. The types and properties of RCA, binder and aggregates, along with the amount of RCA and hydrated lime incorporated, play a vital role in the overall performance and could be attributed to the discrepancies found in the results of the selected studies. Therefore, it is of significance to further investigate the role of these attributes on the performance of asphalt mixtures.

Additionally, due to the intricacies found in pavement engineering stemming from the viscoelastic behavior of asphalt binder on a multilayer level, authorities and governmental bodies have urged contractors and transportation agencies to include accelerated pavement testing at the design and decision-making level.

Accelerated pavement testing can take trivial forms such as plate-loading devices, to technologically advanced, full-scale test tracks. In the context of cost, the AASHTO road tests that concluded in 1962 had an expenditure of $27 million - $81 million in present value. While decreasing operational costs to $100,000 - $120,000, full-scale testing was a leap forward for engineers to effectively test pavement responses not attainable in other tests. However, the process involved in preparing, constructing and instrumenting test tracks can be prohibitively expensive. The current study also demonstrates the assembly and instrumentation of a cost-effective accelerated pavement tester according to the AASHTO T 324 guidelines and can assess rutting deformation potential for various asphalt mixes and be utilized for applications that can support transportation agencies and contractors with financial assessments based on performance metrics.

### 2.7. Research Questions & Objectives

Consequently, this research will supplement the existing literature by tackling the following questions:

1. How adequately can the proposed accelerated pavement tester assess rutting and moisture susceptibility?

2. How will the change in binder content and air voids, based on the allowable deviations by DOTs, affect permanent deformation?
3. How justifiable are current penalties set by States' department of transportation construction guidelines for violations in constructed allowable binder content and air voids?
4. How would the addition of RCA aggregates, RCA mineral filler, and hydrated lime affect the rutting potential and moisture susceptibility?

The main tasks of this thesis work can be summarized as:

1. Prepare an accelerated wheel tester that can be used as a reliable performance-based testing equipment to predict rutting potential for different asphalt mixes.
2. Investigate the variation of binder content and air voids on rutting susceptibility based on allowable deviations set by DOTs and set performance-based pay factors.
3. Investigate the effect of incorporating RCA, hydrated lime and RCA filler on the rutting potential and moisture susceptibility of asphalt mixtures.

# CHAPTER 3

# METHODOLOGY

The primary objective of an accelerated pavement tester is to examine the rutting susceptibility of bituminous mixtures. To do so, an accelerated pavement tester was built at the American University of Beirut, adhering to the standards of AASHTO Designation: T 324-04. The process involved assembling the body of the machine, installing a depressurized rubber tire, configuring a temperature control system, setting up an impression measurement system, a wheel pass counter, and specimen fabricated to be mounted on polyethylene molds. Several conditions were investigated using the accelerated tester. Mixtures were prepared with variations in their binder content, air void content and different additives and polymers were incorporated into mixtures to evaluate their rutting potential and moisture susceptibility.

## 3.1. Materials

### *3.1.1. Aggregates*

Two types of aggregates were used in this study: (1) Lebanese limestone aggregates obtained from local Lebanese quarries and (2) coarse recycled concrete aggregates (RCA). Due to the absence of RCA supply in waste and demolition construction sites that satisfies sample preparation procedure, cylindrical concrete specimens were crushed and then placed into the Los Angeles machine for mechanical abrasion.

### *3.1.2. Binders*

Asphalt mixtures were mixed with two types of binders: (1) non-modified neat binder and (2) Styrene-Butadiene-Styrene (SBS) modified binder.

The neat binder had a Superpave Performance Grade (PG) PG 70-16 while the modified binder had a PG 76-28 “V”. The V notation stands for very heavy traffic based on the multiple stress and creep recovery (MSCR) test.

### *3.1.3. Fillers*

Three types of fillers were incorporated into sample preparation: (1) limestone filler, (2) RCA filler and (3) hydrated lime filler. Limestone and RCA filler consisted of sieving and collecting material passing sieve #200. Hydrated lime was obtained from Holcim, a Lebanese construction supplier.

## 3.2. Machine Instrumentation

The entire body of the accelerated pavement tester is made of steel. The specimens to be tested are placed on top of polyethylene (polyamide) plates that are cut and customized to tightly fit in asphalt briquettes in a manner that restricts the movement of the specimens in both lateral and longitudinal direction. The machine is presented in figures 5, 6, 7 and 8.

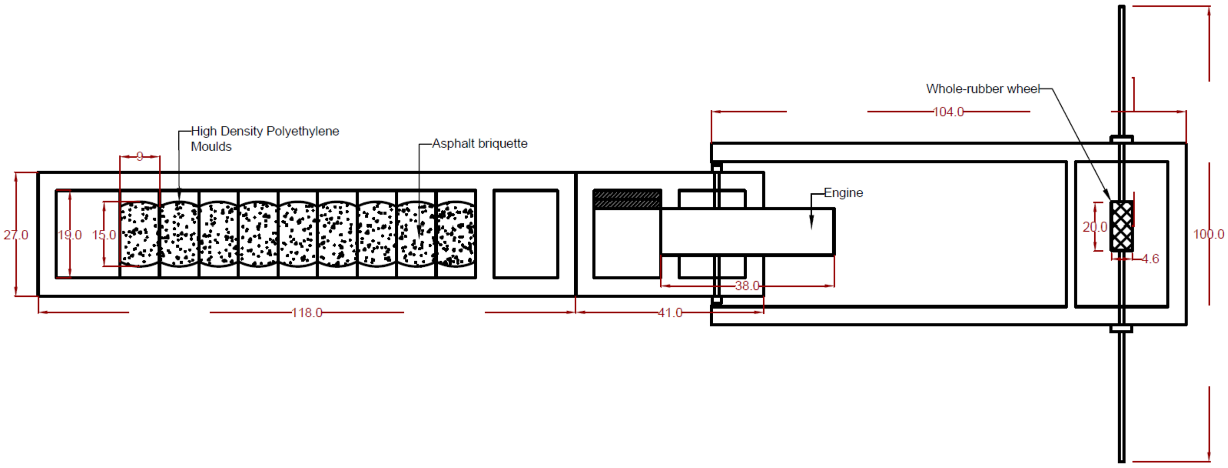


Figure 5 Top view sketch of the APT

The machine is powered by a three-phase motor by Guanglu Eelectrical Co. Ltd, of type GL-802-4 B3, and connected to a controller panel which allows for the adjustment of the speed and controlment of the wheel movement.

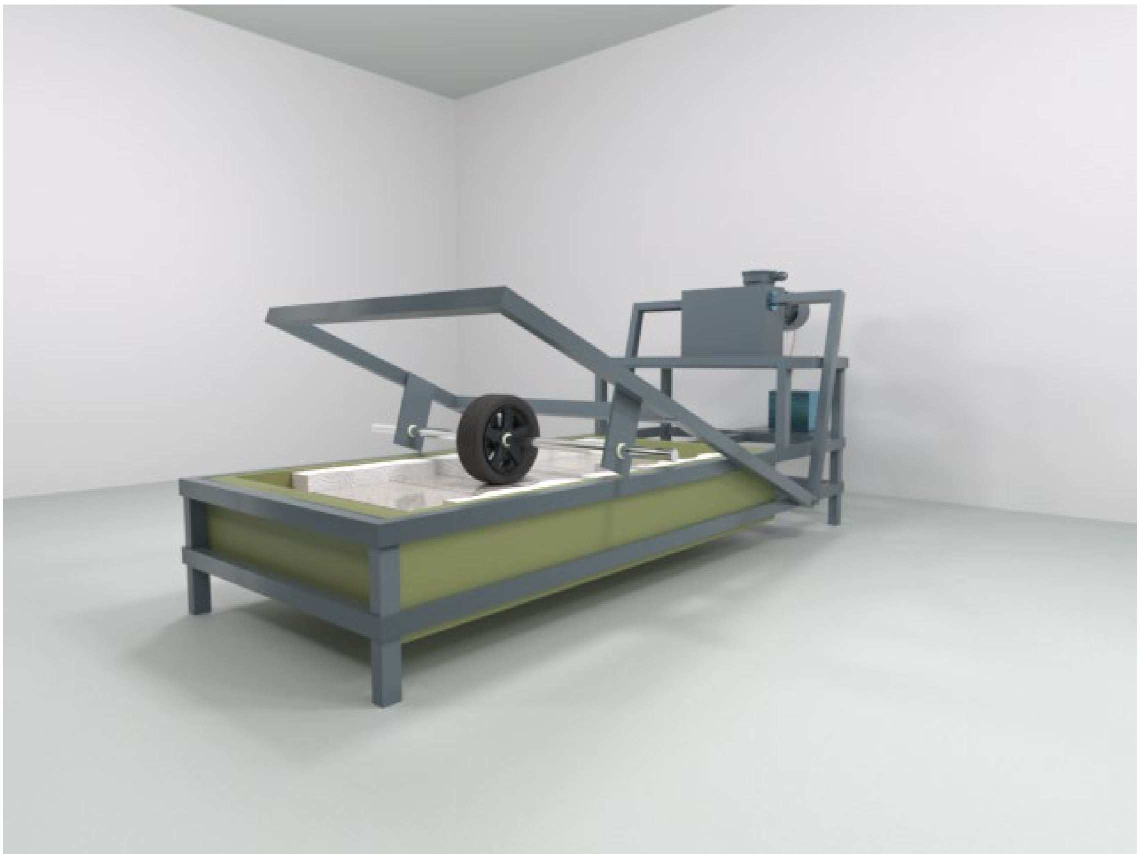
Figure 6 3D Max rendered image of the APT

Inside of the machine, an anti-rust paint-coated rectangular steel mold is placed, having dimensions of $118x27x20\ cm$. A concrete slab is placed inside to provide support to the polyamide plates that have the briquettes fitted inside. The concrete slab is extended to the length of the cumulative length of the three polyamide plates. The polyamide plates occupy a height of 6 $cm$ – hence leaving 4 $cm$ as additional space.

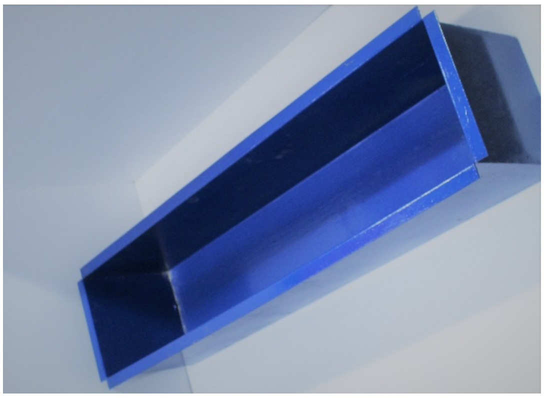

Figure 7: Rectangular steel mold

Figure 8 Side view of the APT

### *3.2.1. Machine Stability*

The ART can sustain weights up to two hundred kilograms. Although the adopted loading is at two hundred pounds, the ground at the structural laboratory at the AUB is epoxy coated and provides decreased friction between the ART legs and floor. Therefore, the following steps were taken: (1) supports are installed under the length of the machine, (2) rubber mats are placed under the machine to increase the contact friction between the machine legs and the floor, and (3) the machines' legs are placed in rubber chair leg caps. The components are shown in figure 9.


Figure 9 Practices for APT stability

### *3.2.2. Polyamide Plates*

Polyamide is a material that is both durable and exhibits high strength, and it is typically used in manufacturing industries. To fabricate the required plates in a shape that is suitable and fitting to the asphalt briquettes, different pieces of polyamide plates are sawed, cut and assembled. As shown in figure 10 and figure 11, the final assembly is connected by bolt connections on the left and right sides and also from the bottom side to ensure sufficient locking. In this experimental work, polyamide plates are used to tightly hold the asphalt specimens that are subjected to reciprocated wheel loading and are placed on top of a concrete slab.

Figure 10: Top view of polyamide plates

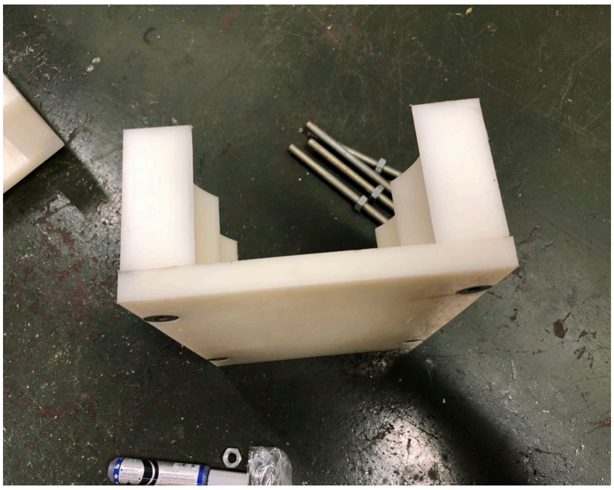

Figure 11: Side view of polyamide plates

### *3.2.3. Tire Selection*

According to the AASHTO T 324 guidelines, the specifications include that the wheel should have dimensions of $203.2\ mm$ diameter and $47\ mm$ width. Moreover, typical contract stresses between asphalt pavements and conventional vehicle tire are approximated at $100\ PSI$. Given that, three types of wheels were experimented with when selecting the suitable installment for the accelerated rut tester.

3.2.3.1. Steel Wheel

A steel wheel having a diameter of $20\ cm$ and width of $5\ cm$ was first used as shown in figure 12.

Figure 12: Type 1 | Steel wheel

However, in actual road trafficking by vehicles, asphalt pavements are in contact with rubberized vehicle tires and not steel. Therefore, to mimic the behavior of the contact area between pavement sections and vehicles, the option to use rubber tires was explored.

3.2.3.2. Air Pressurized Wheel

Figure 13 shows the air pressurized wheel that was trialed. Even though the contact area between asphalt specimens and the wheel surface is rubber, upon wheel load applications of two hundred pounds, the air pressure inside the wheel tended to decrease and deflate; consequently, changing the contract area with the asphalt specimens, in return affecting the imposed contract stresses.

Figure 13 Air pressurized wheel

3.2.3.3. Whole-Rubber Wheel

Finally, the third option was to use a whole-rubber wheel (figure14). Removing the possibility of deflation during load cycles while heavily loaded, this type of wheel ensures that the contact area between the asphalt specimens and wheel is constant throughout testing. Also, it can serve as an adequate replicator of real vehicle trafficking and impose similar stresses with its rubber body.

Figure 14: Depressurized tire: cross section view

### *3.2.4. Contact Stresses*

After installing the proper tire, the contact stresses must be checked if they fall within the acceptable and reasonable limits to adequately resemble real trafficking. First, to obtain the contact stresses, the contact area was calculated through image processing using MATLAB. Moreover, contact between irregular surfaces, such as asphalt pavements and rubber, will result in a significant amount of gaps in contact. Pressing rubber into asphalt pavements will indefinitely increase the actual contact area. With that rationale in mind, as the accelerated pavement tester is loaded with additional weights that can reach up to two hundred pounds, the contact area between the whole-rubber wheel and asphalt specimens will be slightly altered between different amounts of load. To address this issue, contact areas were obtained for each load interval of forty pounds.

To calculate the contact area, the whole-rubber wheel is coated with a colored powder. Then, white adhesive paper is used and placed under the wheel's path. Next, the tire is lowered until in full contact with the adhesive paper, coating it with a colored pattern of the contact area. A total of four readings are taken for each weight. The below can be summed in table 2

Table 2 Summary of contact area readings

| | Area ($cm^2$) | | | | | |
|---|---|---|---|---|---|---|
| **Weight (lb)** | No weight | 40 lb | 80 lb | 120 lb | 160 lb | 200 lb |
| **1st Reading** | 9.802 | 9.04 | 10.4583 | 12.2466 | 11.9348 | 10.328 |
| **2nd Reading** | 11.16 | 11.7906 | 12.3203 | 10.8228 | 13.2837 | 12.078 |
| **3rd Reading** | 10.45 | 13.17 | 10.32 | 10.7804 | 12.5545 | 11.2997 |
| **4th Reading** | 10.14 | 11.73 | 11.34 | 10.479 | 12.2222 | 11.605 |

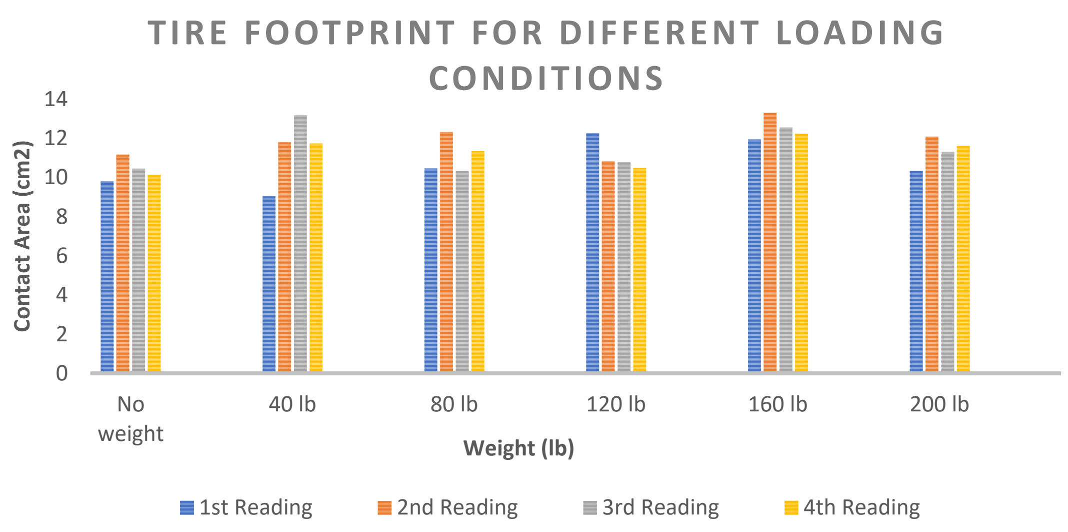


Figure 15: Contact areas at different wheel loading

To accurately measure each one of the contact area readings, a code was written in MATLAB. Briefly, the code works by extracting an image of the adhesive paper with the contact area. Then, the total number of pixels are calculated for both the whole image including white space and the contact area pattern. Next, the ratio between these pixel values is calculated and the area of the contact area relative to the whole picture is measured. The code can be found in the Appendix.

An analysis of variance (ANOVA) test was conducted to investigate if the population means between the different weight conditions are statistically different. The ANOVA results are presented in table 3

Table 3: ANOVA test on the contact area readings for different weight conditions

| ***Source of Variation*** | ***SS*** | ***df*** | ***MS*** | ***F*** | ***P-value*** | ***F crit*** |
|---|---|---|---|---|---|---|
| **Between Groups** | 9.482577 | 5 | 1.896515 | 2.000682 | 0.127314 | 2.772853 |
| **Within Groups** | 17.06282 | 18 | 0.947935 | | | |
| Total | 26.5454 | 23 | | | | |

For a type I acceptable error of 5 percent, the P-value is 0.127 which is greater than 0.05, this means that there is not sufficient evidence with type I error of 5 percent to reject the null hypothesis that the population means of the groups are statistically not different. Therefore, it can be said that all the recorded contact areas for the different load configuration are statistically indifferent and can be assumed equal. Taking the average of all the data, the resulting contact area is 11.306 $cm^2$ . Consequently, for a load of 200 lb., the contact stress assuming that the load is a point load is

$$Equation\ 1: \delta = \frac{P}{A} = \frac{200}{1.7524335} = 114\ PSI.$$

Equation 1. Contact stress calculation

### *3.2.5. Rut Depth Measurement System*

To measure rut depth in terms of wheel cycles, a Linear Variable Differential Transformer (LVDT) was used. It is an electromechanical transducer which can measure linear displacement. As such, an aluminum assembly was designed that can be mounted on the APT in various locations and records the linear displacement occurring over wheel passes (figure 16).

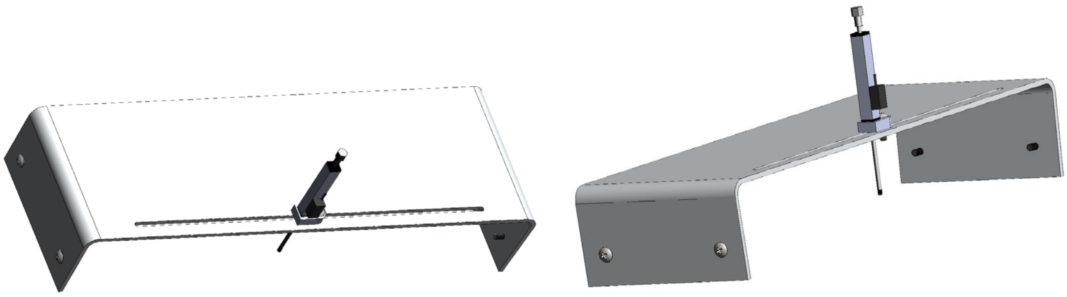

Figure 16: Assembly of rut depth measurement produced in SolidWorks

The circular opening channel allows for the movement of the LVDT in the transverse direction but restricts its movement in the longitudinal direction. This is achieved by both the bolt connection between the aluminum plate and the LVDT and the circular channel. The LVDT is connected to a data acquisition system that can record the change in linear displacement in terms of electrical current and transform it into metric units (inch). Figure 17 showcases the LVDT’s connection with the data acquisition system.

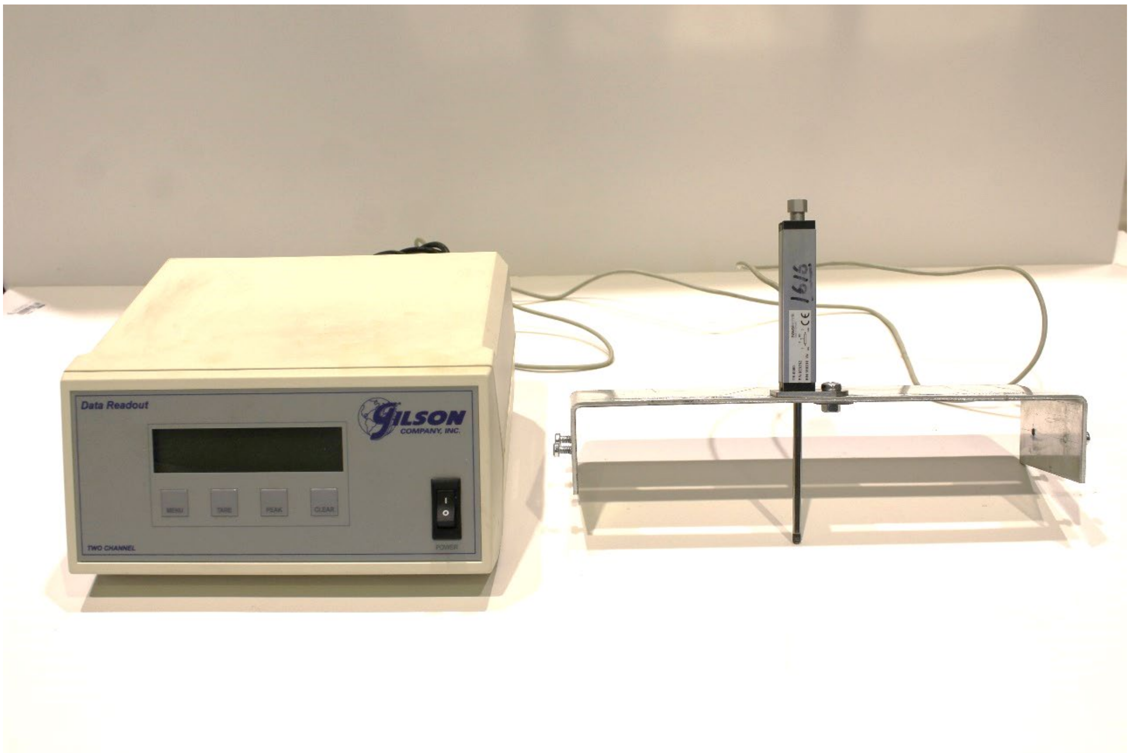


Figure 17: Data acquisition system connection with the LVDT

The bolts on the sides are installed to fix the assembly, once mounted, in the same location every time a measurement is taken. Once the locations are set, the LVDT will transition downward until it hits the surface of the asphalt specimen. After the initial reading is taken, measurements at one thousand cycle intervals are taken to record the change in the linear displacement of the LVDT – which is the permanent deformation occurring at each sample at the midway of the wheel path. Figures 18 and Figure 19 demonstrate the set up at reference (prior to testing) and after testing.

The LVDT has an electrical measuring range of 52 mm, and has a resolution (accuracy) of 0.00254 mm. An important parameter to look for in LVDTs is their repeatability; the ability of a sensor to reproduce the same output under constant operating and environmental conditions. The repeatability of the used LVDT is within $\pm 0.002$ mm – ensuring that minimal static error is occurring when recording multiple rut depths.

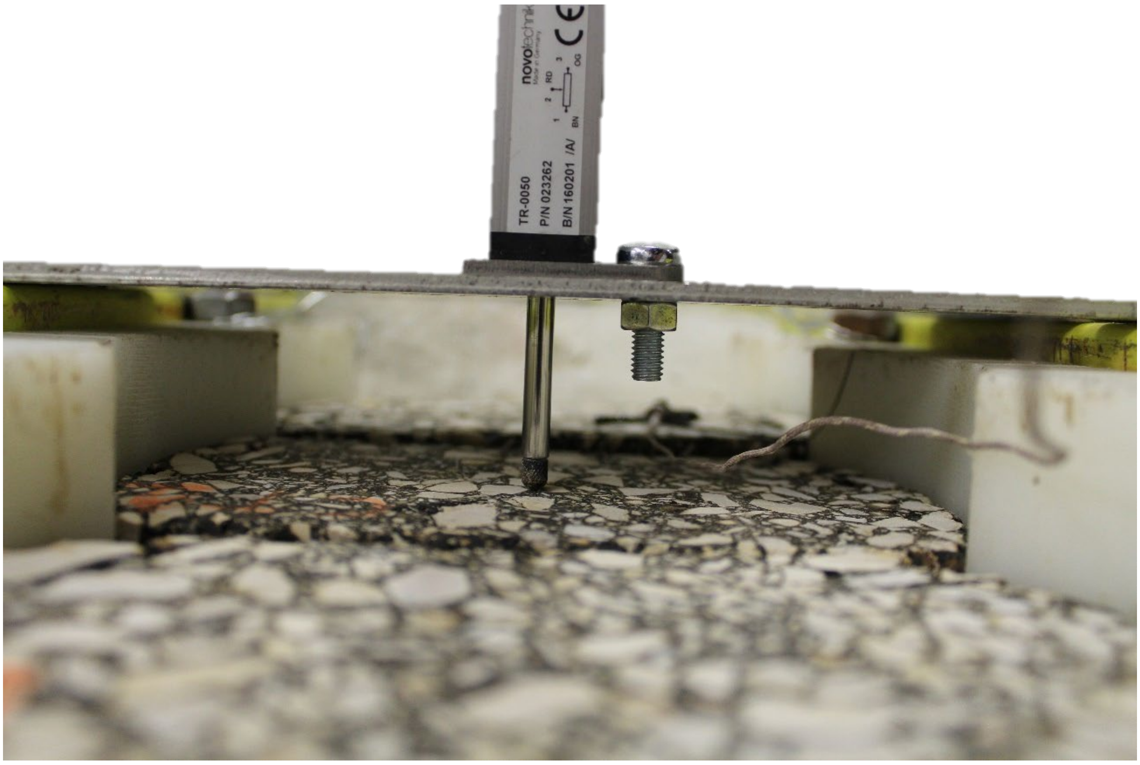


Figure 18: LVDT reference measurement

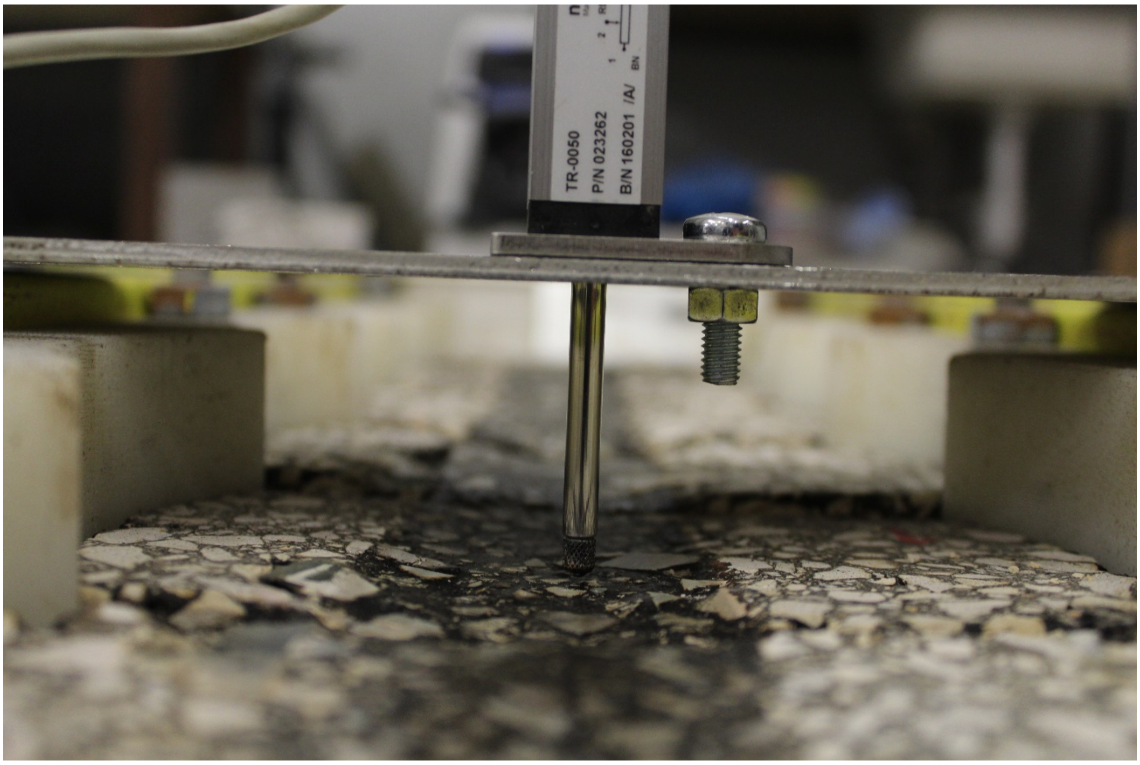


Figure 19 LVDT measurement after testing

### 3.3. Temperature Control System

Bituminous materials are highly susceptible to both temperature and time according to the time-temperature superposition. As such, the ambient temperature and vehicle speeds have a significant effect on asphalt pavement.When the temperature increases and loading speed decreases, the stiffness and strength of asphalt concrete is immensely weakened. In actual road conditions, the pavement temperature is typically measured at 2 cm depth where it is at its highest (B.B. Teltayev & E.A. Suppes). Based on the set guidelines, the recommended testing temperature is at 40 Celsius for both dry and wet testing conditions.

Given the machine's geometrical shape and technical functionality, the usage of infrared light bulbs was explored. These bulbs can radiate heat at the focal point of 160℃ Since the target temperature is at 2 cm into the pavement surface, two dummy specimens were drilled 2 cm and 4 cm in depth. A thermocouple was then inserted into each drilled circular channel and then sealed with bitumen and filler. Next, a second thermocouple was placed and fixated on the surface. Three dummy specimens, connected to thermocouples, were placed at the extremities of the test bed, i.e., the first, second, and ninth specimen placements to account for variable wheel loading as the wheel approaches and leaves these points. To configure the best placement for the infrared light bulbs, several configurations were evaluated. The infrared light bulbs are hanged unto steel hangers and clipped into it at a specific height. The configurations took into consideration (1) the location of the base of the steel hanger, (2) the situated height of the clipped bulb, (3) the angle at which the bulbs are directing towards the test bed, and (4) experimenting with preheating the polyamide plates with the asphalt briquettes in an oven at 40 ℃ for an hour prior to placing them on the test bed.

Knowing that the surface temperature is always higher than the inside of the samples, the final set-up needed approximately an hour for the core temperature to stabilize uniformly without the need to preheat the samples in an oven. The main target of the trial configurations was to ensure that the heat radiated from the bulbs is sufficient to heat and maintain the entire asphalt briquette to a temperature of 40 °C.

Monitoring the samples' temperatures using a thermometer, figure 20 demonstrated the final set-up that stabilized the temperature at 40 °C throughout the geometry of the sample.

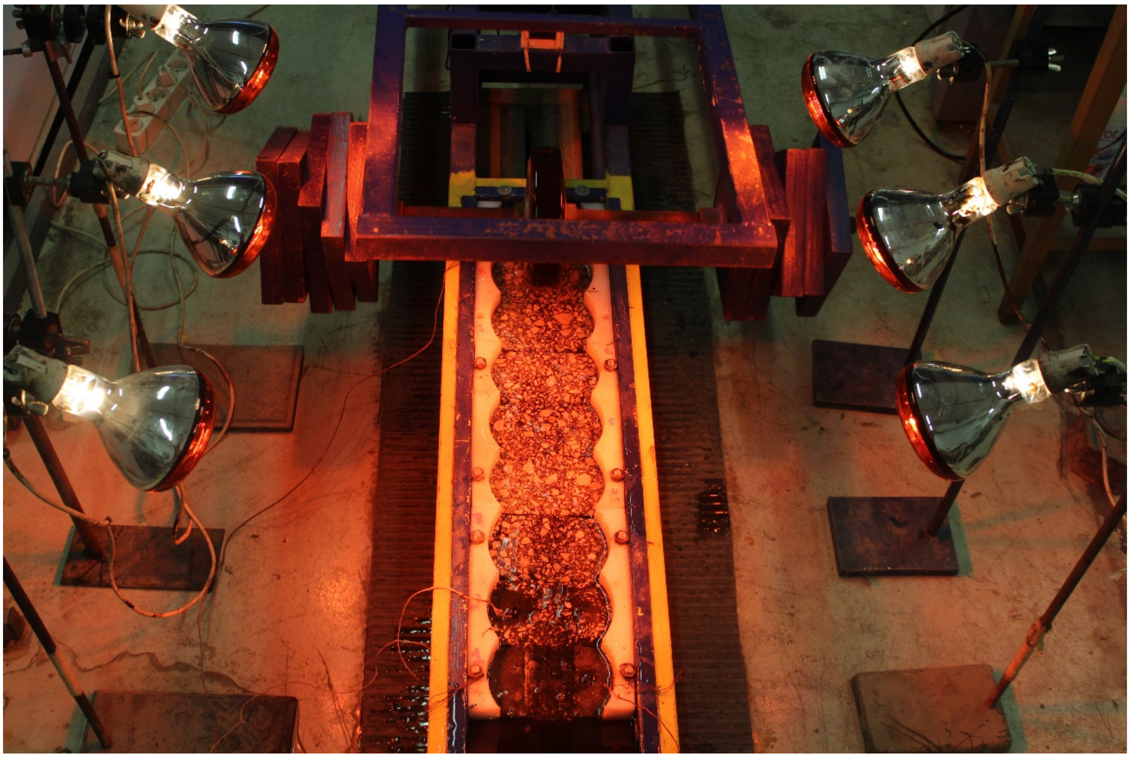

Figure 20 Infrared light bulbs set-up with thermocouple installation on the asphalt briquettes

To transfer the water into the test bed and fill it, a Masterflex L/S High-Performance Precision C-Flex® ULTRA Pump Tubing in compatibility with Masterflex L/S pumps (figure 22) was used. The tube was inserted into the test bed, while the other end was submerged into a water bath (figure 21) to withdraw water at a temperature of 40 ℃ to facilitate the stabilization of the overall temperature of the asphalt briquettes.


Figure 21: WiseBath© water bath


Figure 22: Masterflex pump

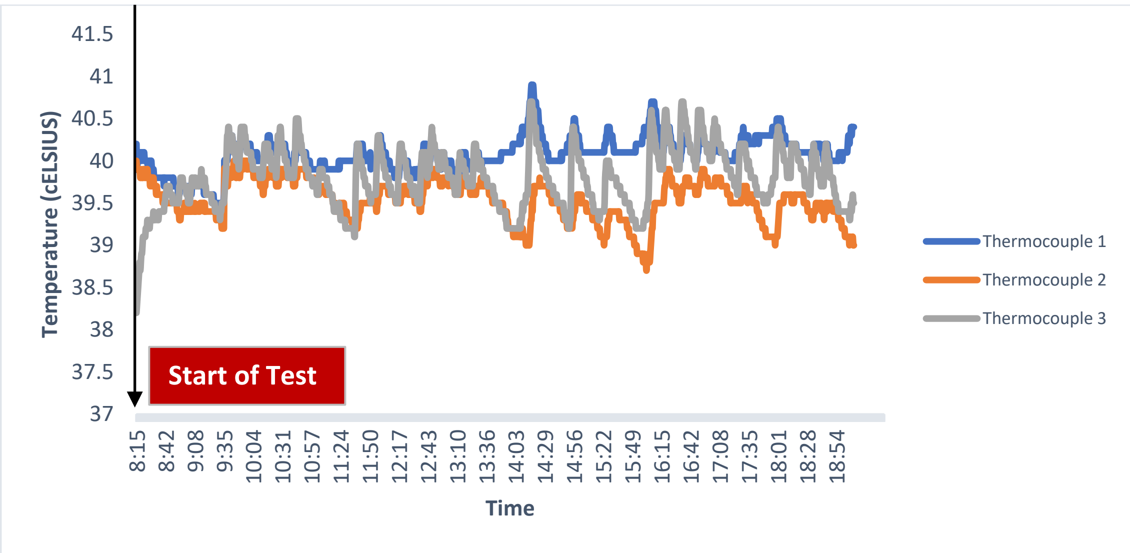


Figure 23 Sample graph of the temperature monitoring using infrared light bulbs

### *3.3.1. Surface Temperature Calibration Using a Thermal Imager*

Using the infrared light bulbs to provide sufficient heat to raise the temperature of the asphalt briquettes, the surface temperature is generally higher. To ensure that the thermocouples are accurately measuring the temperature of the samples without any interference, the thermocouples are drilled into the samples deep enough to mitigate any intrusion of air or movement on the measured temperature. On the surface, a thermal imager is used periodically to take the temperature and compare with the thermometer readings to affirm that there's no discrepancies or error in both measurements. The thermal camera used is from Milwaukee with a thermal sensitivity of 0.1℃ and range of $[-10℃, 350℃]$ (figure 24). Consequently, the surface temperature measurement is presented in figure 25 and the output image of the camera for the asphalt briquettes is taken after trafficking in one APT run and shown in figure 26

Figure 24 Thermal imager

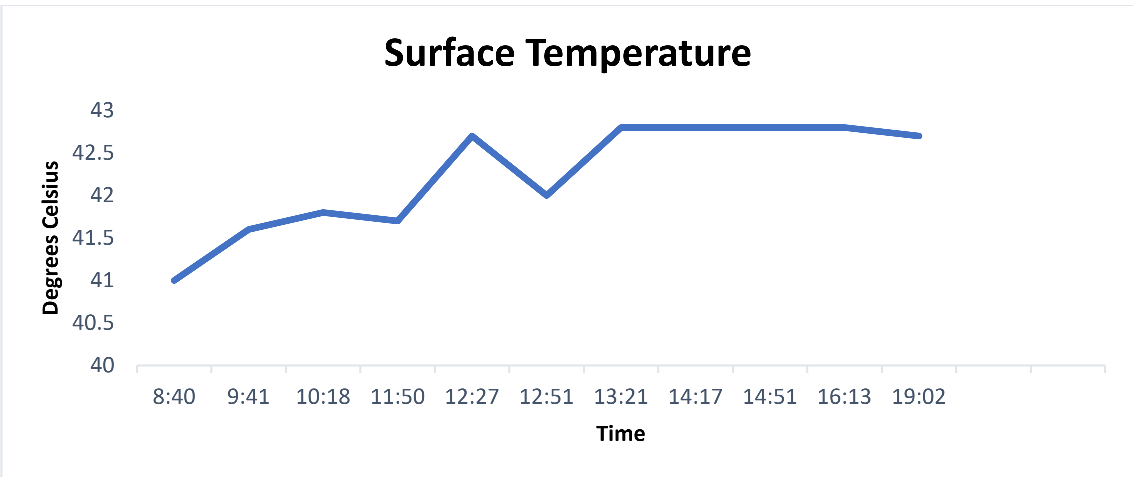


Figure 25 Surface temperature taken using a thermal imager

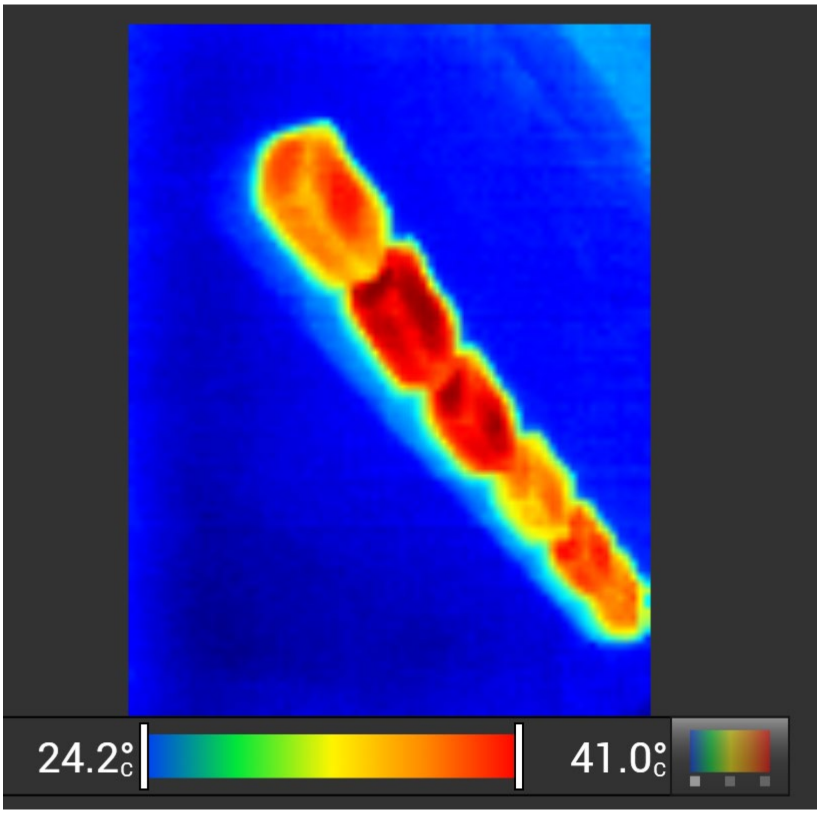


Figure 26 Asphalt briquette temperature throughout its geometry

### 3.4. Sample Fabrication for APT trafficking

Sample fabrication of the briquettes started with preparing the batching weight and batching the required amount of coarse and fine aggregates. Then, the mixing and compaction temperatures of the binder used were obtained using the viscosity rheometer. The mixing temperature was 155.25 °C and the compaction temperature was 145.5°C. The binder used in this study was of PG-70-16 according to the Dynamic Shear Test. After drying the batched aggregates for 24 hours, the asphalt mixtures were mixed and compacted according to the values obtained from the viscosity rheometer to ensure decent workability of the binder and adequate coating of the aggregates by the binder.

The resulting Superpave Gyratory Compactor (SGC) sample has a diameter of $150\ mm$ and a height of $120\ mm$. Next, the sides of the SGC sample were cut off so that a width of $9\ cm$ remain. Then, $1\ cm$ was sawed from the upper and bottom sides to remove irregularities in compaction and guarantee smoothness of the sample, producing a sample that is $10\ cm$ in height. Then, the sample was cut in half to result in two asphalt briquette samples of dimensions $150x90x50\ mm$ that were fit into the polyamide plates. Figures 27 and 28 describe the sawing process that produces the asphalt briquettes from the SGC sample.

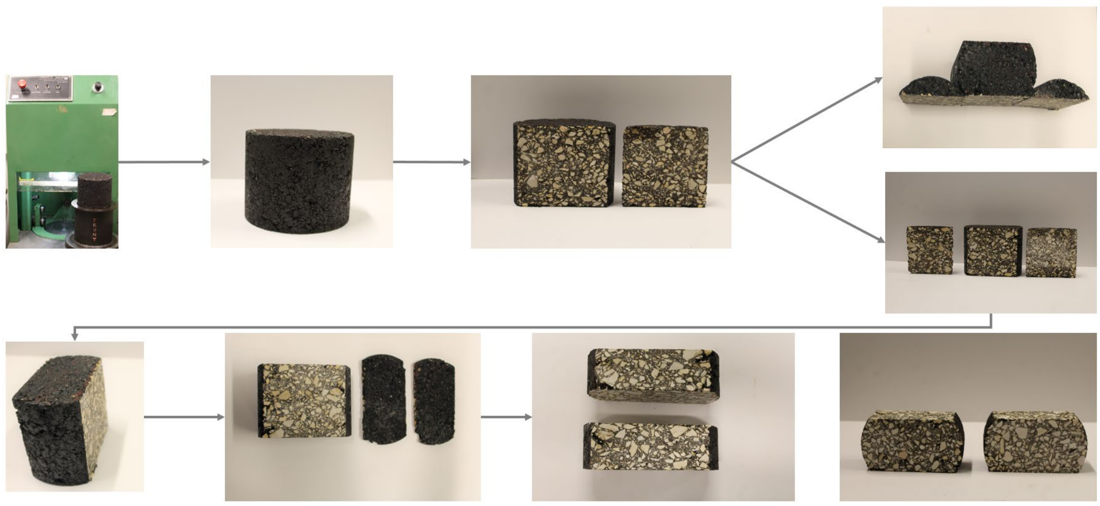

Figure 27 Process of briquette-shaped specimen fabrication for APT trafficking

Figure 28 Briquette samples after sawing

### 3.5. Volumetrics

Typically, asphalt mixes are designed and prepared with an air void percentage target of 4% to replicate the case in the field after compaction. However, for accelerated pavement testing, asphalt specimens should typically have an air void percentage between 6% and 8% according to AASHTO T 324. This air void percentage allows for the accelerated detection of rutting deformation under APT and reflects the pavement as placed in the field. Additionally, it is important to obtain similar air void percentages between the fabricated asphalt briquettes in order to isolate the effect of air voids on the rutting susceptibility of mixes, and to capture the effect of different additives and modifiers incorporated into asphalt mixtures.

The maximum specific gravity and bulk specific gravy are computed using the Instrotech CoreLok™ . Consequently, the air void percentage can be calculated from

Equation 2: $\% \, Air \, Void = \left(1 - \frac{G_{mb}}{G_{mm}}\right) * 100$

Equation 2: Air voids calculation

To target an air void percent of $\pm 7\%$, different batches were mixed, and asphalt briquettes were prepared to obtain their volumetrics. It was concluded after trial and error that there is a difference of approximately $1.5\%$ in air content between the SGC samples and its product of asphalt briquettes. It is known by Superpave mix design that the main factors that alter the air content of asphalt mixtures are the compaction height and batching weight of the sample. To target $8.5\%$ in the SGC sample, different iterations were done on the batching weight given that the height should be fixed at $12\ cm$.

## 3.6. Testing Conditions

Using the APT and following the guidelines of AASHTO T324, testing of asphalt briquettes is undertaken in dry and wet conditions

### *3.6.1. Testing in a Dry State*

For dry testing, the fabricated asphalt briquettes are placed into the test bed of the APT and the infrared light bulbs are set up. Prior to testing, the samples are heated for 2 hours until the temperature of the entire asphalt briquettes throughout the test bed is stabilized at $40°C$. The test is then run for 12 hours or the equivalent of 11,000 loading applications while simultaneously measuring rutting depths at different number of cycles.

### *3.6.2. Testing in a Wet State*

As for wet testing, the same steps are followed in the case of dry testing. However, prior to testing, water is heated to $40°C$ using a water bath, which is then transferred into the test bed and submerging the asphalt briquettes. In order to maintain the temperature and ensure that the temperature is constant along the samples and within the core of the sample, the infrared light bulbs set up is utilized. The time until temperature stabilization and moisture conditioning was around 3 hours prior to starting the test.

# CHAPTER 4

# EXPERIMENTAL PLAN

For the purpose of this study, several tests were conducted to better evaluate asphalt mixtures using the APT at the mixture level and at operational level. The below section describes the different test conditions and their associated experimental work.

## 4.1. Application 1: Effect of Air Content on Rutting Susceptibility

The first application consisted of testing three asphalt mixtures that exhibit the same gradation and materials but possessed different air content. Table 4 summarizes the properties of the asphalt mixtures that were fabricated for testing.

Table 4 Application 1: asphalt briquettes properties for APT trafficking

| Condition | Replicate | Aggregate Type | Binder Content (%) | Air Content (%) |
|---|---|---|---|---|
| **C1** | R1 | Limestone | 4.80 | 4.4 |
| | R2 | | | 4.4 |
| **C2** | R1 | | | 6.2 |
| | R2 | | | 6.8 |
| **C3** | R1 | | | 8.0 |
| | R2 | | | 8.9 |

The main purpose of this experimental test so to investigate the effect of air void percent in asphalt mixtures on the rutting potential of mixes. Additionally, it is of interest to also see whether the APT can capture the effect and produce reliable results.

## 4.2. Application 2: Effect of Binder Content on Rutting Susceptibility

### *4.2.1. Evaluating Penalizable Metrics Based on DOTs Standard Specifications*

The second application was composed of three asphalt mixtures that are like those used in application one; however, different binder contents were adopted based on the standard specifications for roads and construction.

After reviewing the different standard specification for roads and construction for different states (Florida, 2021; Illinois, 2016; Pennsylvania, 2020; Texas, 2014; North Carolina, 2018; Massachusetts, 2020; Delaware, 2020; Indiana, 2022; Colorado, 2019), they typically set mix design and construction specification for asphalt pavements that the contractor is contractually obliged to follow. In the scenario in which the contractor under delivers or violates any of the conditions enlisted in the agreement between them and the state, the contractor is penalized. For example, the state of Florida, in terms of binder content for master production range, the allowable tolerance is $\pm 0.55\%$, while it is $\pm 0.3\%$ for the state of Texas. Table 5 represents the construction requirement tolerances for different states. Each state sets its own regulation and protocol on how to alter payments and pay factors due to contractual violations in the construction requirements. For example, for the state of Florida, the pay factor could go as low as $0.55$ for binder content deviation up to $2.5\%$.

Table 5 Construction requirement tolerances

| State | Binder Content (Percent) | Air Voids (Percent) |
|---|---|---|
| **Florida** | Target $\pm 0.55$ | 2.5 |
| **Texas** | Target $\pm 0.3$ | 1.40 |
| **Pennsylvania** | Target $\pm 0.5$ | 2 |
| **North Carolina** | Target $\pm 0.7$ | 1 |
| **Massachusetts** | Target $\pm 0.35$ | 1.2 |
| **Colorado** | Target $\pm 0.3$ | $NA$ |
| **Illinois** | Target $\pm 0.3$ | 1.2 |
| **Delware** | Target $\pm 0.4$ | 2 |
| **Indiana** | Target $\pm 0.7$ | 1 |

As such, it can be observed that most states, when penalizing contractors, the main criteria is typically set after taking several cores from different lots and tested depending on the states' specifications. Then, the values of the binder content and air voids along with other volumetric properties are evaluated whether they fall within the acceptable tolerance limits, which in return plays a vital role in determining the pay factor.

### *4.2.1. Acceptable Control Limits and Tolerances to Performance-Based Pay Factors*

Typically, most agencies use a set of control limits that the contractor's work should fall within after construction of asphalt pavements. Regular inspections are carried out throughout different lots to ensure conformity. For rutting, the asphalt concrete construction parameters are influenced by: (1) asphalt content, (2) air-voids, and (3) aggregate gradation. Performance-based approach in deciding pay factors, on the other hand, emphasizes on the pavement structural attributes and mix that prominently affect the performance. Additionally, it highlights the importance of homogeneity of materials production and placement.

The performance-based approach utilizes a relative performance concept of the as-constructed mix for a specific pavement metric. For example, for newly constructed pavements, a performance-based parameter can be adopted as an evaluating tool in quality control protocols. To illustrate, the accumulated permanent deformation and corresponding ESAL number that occurs during the first year of the pavement life could be weighted against these metrics in a conventional asphalt pavement structure. Thus, this qualifies asphalt pavements, regardless of its target values, for evaluation measures that depend mainly on achieving the desired performance level and satisfactory performance-based parameters, such as rutting and fatigue.

Given the above, the experimental plan included in this application consisted of preparing asphalt briquettes that vary in asphalt content, which are summarized in table 6. The asphalt binder deviation values of the mixes were adopted from the tolerances of acceptable pavement mix parameters covered in each of the standard specification of different states. The motivation behind the experimental work is to establish performance-based pay factors for one performance model: permanent deformation.

Table 6 Application 2: Asphalt briquettes properties for APT trafficking

| Volumetric Properties | | | | | Replicates | |
|---|---|---|---|---|---|---|
| Condition | Aggregates | Binder Content | Air Content | | Dry | Wet |
| C1 | Limestone | 3.80 | 6.8 | 7.9 | 2 | 2 |
| | | 3.80 | 7.8 | 7.6 | | |
| C2 | | 4.80 | 7.2 | 7.1 | 2 | 2 |
| | | 4.80 | 7.5 | 6.9 | | |
| C3 | | 5.80 | 6 | 6.4 | 2 | 2 |
| | | 5.80 | 6.8 | 6.5 | | |

The approach to establish the pay factors will use the software RealCost. A deterministic analysis will be conducted on the results of a conventional mix, and the relative performance of the mixes with different binder content, i.e., deviations from acceptable target values set by DOTs, will be used. This relative performance can be translated into monetary values by depending on the following input: (1) pavement design life, (2) annual traffic growth, (3) discount rate, (4) rehabilitation and initial construction cost, and (5) frequency of rehabilitations required, which translates into agency cost repercussions due to the delay or acceleration of next planned rehabilitation

This methodology, as opposed to the one followed by agencies, can either fully penalize contractors for inferior construction or provide bonuses fully for superior construction. Currently, agencies set an incremental reward or penalty depending on the deviation extent from the set target values imposed on contracts. The proposed methodology fully rewards superior construction as adequate performance of asphalt pavements correlates with good material quality and construction practices.

### 4.3. Application 3: Investigating the Rutting and Moisture Susceptibility of Asphalt Mixtures

For the purpose of this study, table 7 summarizes the six different conditions that were set to test for the effect of each added component. Conditions C1, C2 and C3 incorporated two binder types, virgin binder and SBS-modified binder. Additionally, hydrated lime was added as 2% of the total filler of the mix. As for conditions C4, C5 and C6, all had virgin binder PG70-16 used. C4 and C5 both contained 30% of the total aggregates in the mixture as coarse RCA, while the remaining 60% contained limestone aggregates.

However, C5 had 2% hydrated lime added as filler. C6 had 100% limestone aggregates and 100% of the filler as RCA. Four asphalt briquettes were fabricated for each of the six conditions, totaling twenty-four samples. These samples were tested under two states: (1) dry conditions and (2) wet conditions. Each three conditions, yielding twelve samples, are tested in both dry and wet state with six samples in the test bed for each run. For dry testing, the temperature is set at 40 °C. While the same temperature is used for wet testing, the test bed and samples are moisture conditioned for two hours prior to testing to ensure that the temperature is constant throughout the specimens' geometry and that sufficient wetting is occurring at the inside of the sample. To reiterate, all samples had an air void percentage of $7 \pm 1\%$ to ensure that the effect of densification due to air voids is diminished, and the effect of the isolated added component is captured under the APT in terms of rutting resistance and moisture susceptibility.

Table 7 Application 3: Asphalt Briquettes Properties for APT Trafficking

| | **Aggregate Type** | | **Binder Type** | | **Filler Type** | | |
|---|---|---|---|---|---|---|---|
| **Component** | Limestone | Coarse RCA | Virgin Binder | SBS-Modified Binder | Limestone | RCA | Hydrated Lime |
| **Condition** | | | | | | | |
| C1 | 90.6% | X | 5.4% | X | 4.0% | X | X |
| C2 | 91.0% | X | X | 5.0% | 4.0% | X | X |
| C3 | 91.0% | X | X | 5.0% | 2.0% | X | 2.0% |
| C4 | 60.6% | 30.0% | 5.4% | X | 4.0% | X | X |
| C5 | 60.6% | 30.0% | 5.4% | X | 2.0% | X | 2.0% |
| C6 | 90.6% | X | 5.4% | X | X | 4.0% | X |

CHAPTER 5

# RESULTS AND DISCUSSION

## 5.1. Application 1: Analysis and Results

After trafficking the asphalt briquettes for 11,000 cycles in both wet and dry conditions, the rut measurements are recorded as a function of load repetitions. Figure 29 and figure 30 summarize the rutting performance for the six asphalt briquettes.

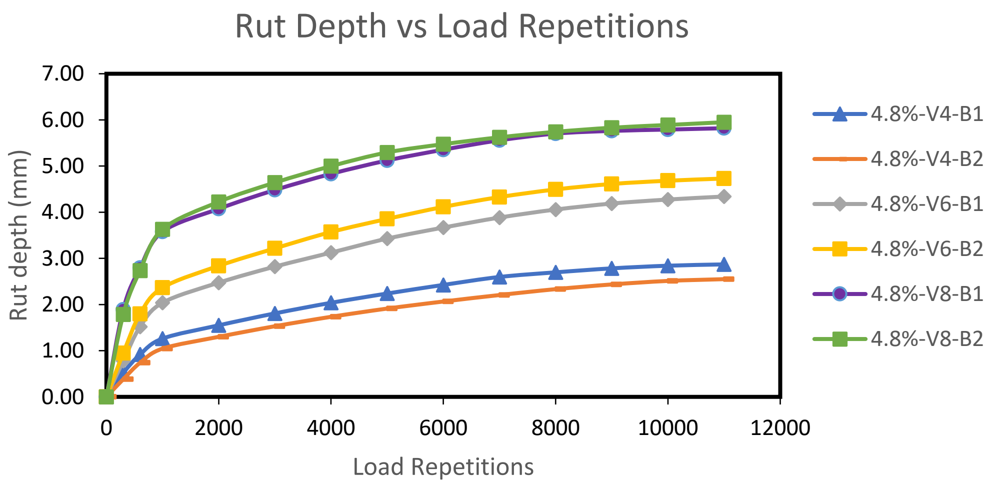


Figure 29 Rut depth as a function of load repetition for application 1: wet condition

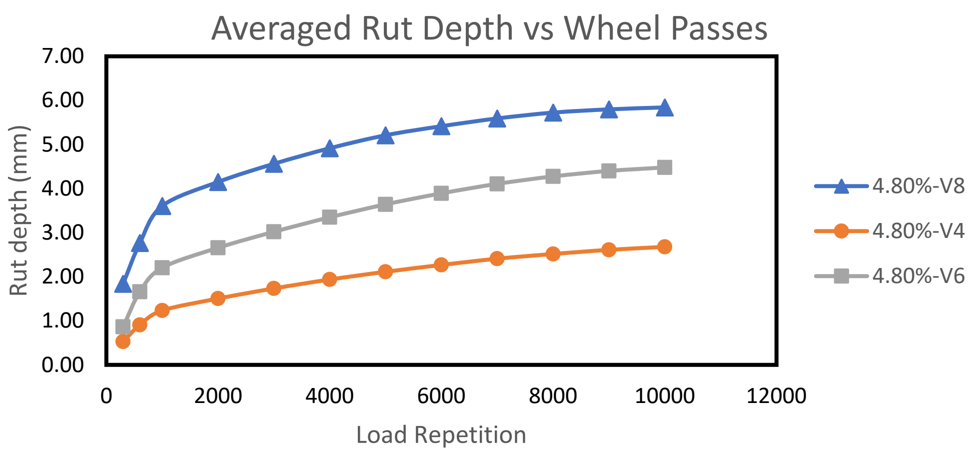


Figure 30 Average rut depth as a function of load repetition for application 1: wet condition

The legend which corresponds to the six asphalt briquettes subjected to APT trafficking refers to the naming of the samples as following: binder content – targeted air voids – and replicate number. It can be graphically observed that asphalt mixtures having a higher air void percentage exhibited the highest rut depth during trafficking – while the opposite is true.

#### *5.1.1. One-way ANOVA on Air Voids*

To ensure that the rutting performance for the three mixes is dependent on its corresponding air voids, and to introduce a statistical measuring tool, a one-way ANOVA analysis was done on the air voids as the independent variable – while the rutting measurements as the dependent variable, after running the APT for 11,000 cycles. The air content in each of the six asphalt briquettes is summarized in figure 31.

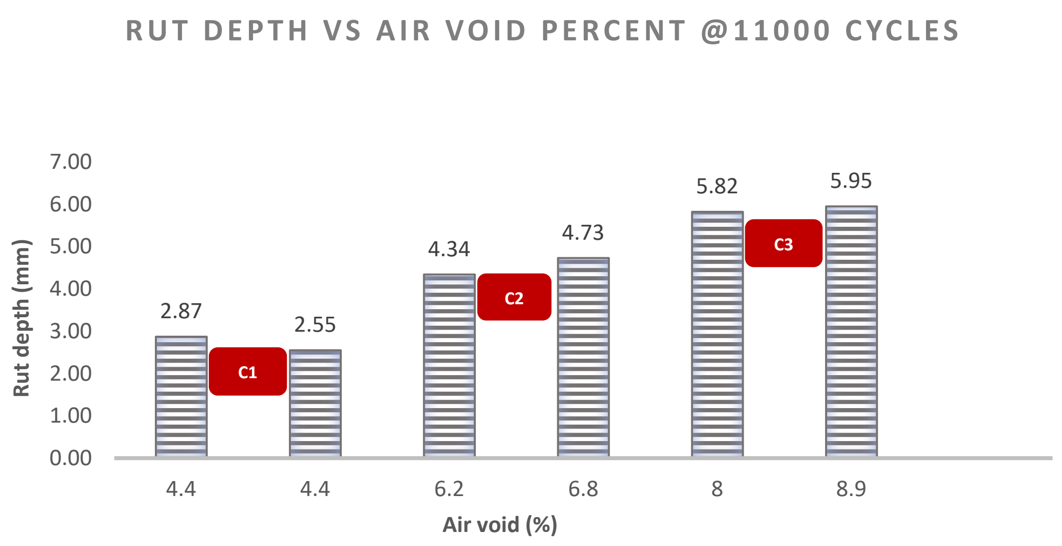


Figure 31 Rut depths as a function of mixes' air voids percentage

Using the ANOVA model, the p-value is $0.000239$, for an $\alpha = 0.05$ or a confidence level of $95\%$, there is convincing evidence that there is an effect of the air voids on the rutting depths exhibited by the samples. As such, the APT can detect these differences between the tested samples and is able to adequately evaluate the rutting performance of different asphalt mixtures. Moreover, it is worth noting that during testing, the mix which had a higher air void percentage had an abrupt rutting occurring at the initial cycles – which can be explained by the densification of the sample as the early loading took place.

### 5.2. Application 2: Analysis and Results

Application two; complementary to application one, aims to characterize asphalt mixtures that violates the standard specifications of different DOTs in terms of binder content – while application one covered the violations in air voids deviation. Two APT runs were conducted: (1) the first run covered testing the samples in dry conditions at a temperature of 40℃, and (2) the second run consisting of testing another set of samples having the same mix but conditioned in a water bath to induce moisture damage. Both runs trafficked the samples for 11,000 cycles, and rut depths were monitored.

The results of the dry trafficking are illustrated in both figures 32 and 33 – while are the results after wet trafficking are illustrated in figures 33 and 34.

The legend corresponds to the binder content – V 1 (dry testing) or 2 (wet testing) – replicate number.

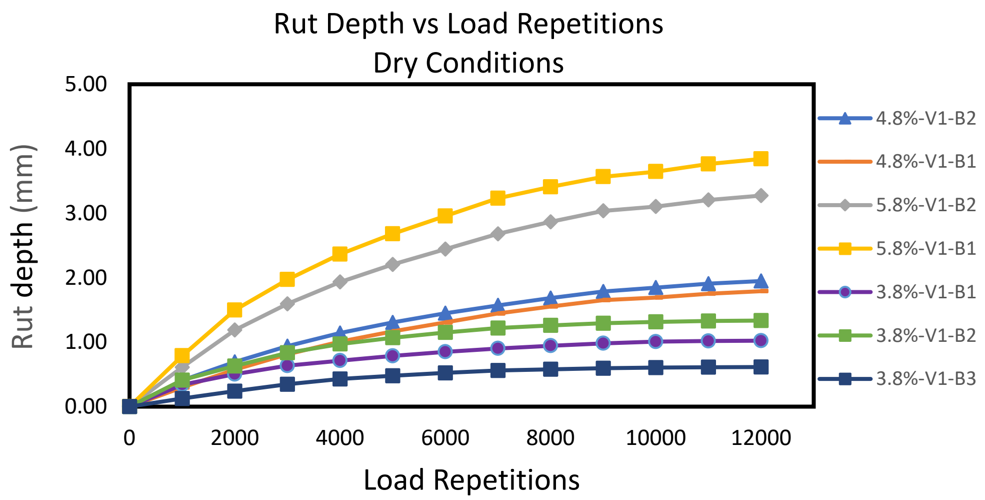


Figure 32 Rut depth as a function of load repetition for application 2: dry condition

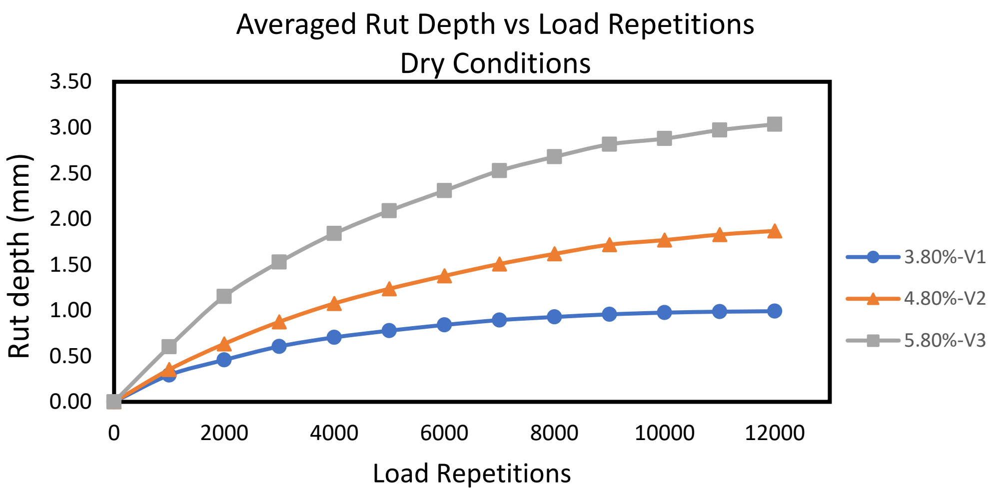


Figure 33 Average rut depth as a function of load repetition for application 2: dry condition

It is noticeable that mixes with the higher binder content exhibit the highest rutting depths; the control mix, which is at 4.8% binder content is moderately rutting, and mixes with the least binder content rutted the least.

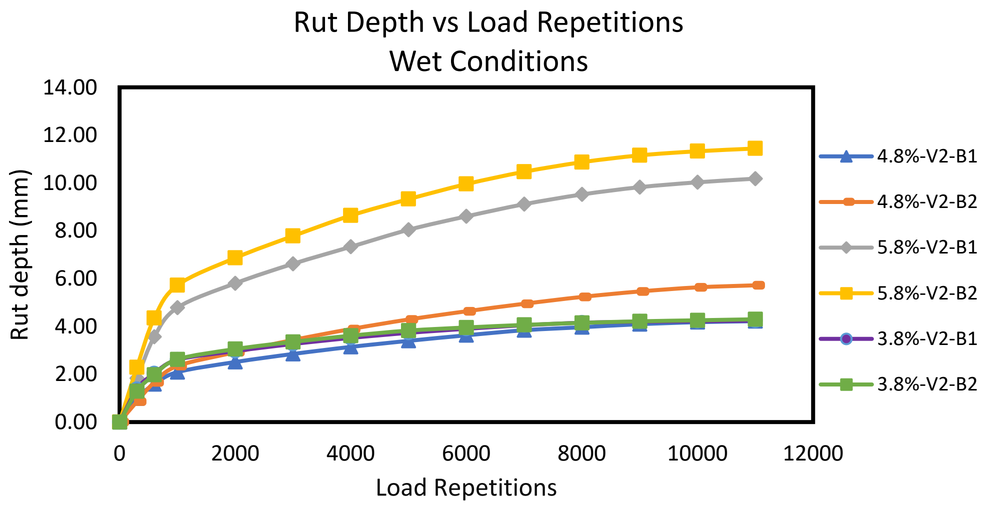


Figure 34 Rut depth as a function of load repetition for application 2: wet condition

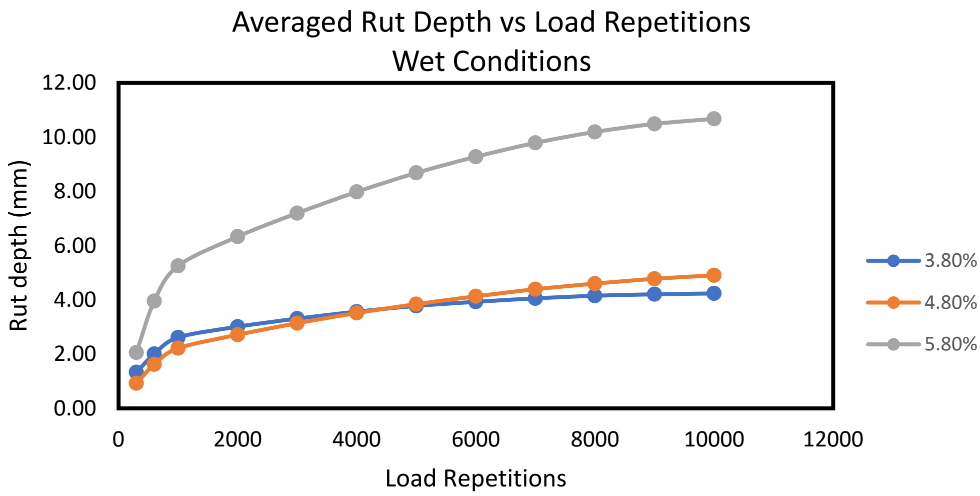


Figure 35 Average rut depth as a function of load repetition for application 2: wet condition

Therefore, it is apparent that the rutting behavior of the mixes is consistent throughout both dry and wet state of testing. It can also be noted that asphalt mixtures with 3.8% binder content tended to rut noticeably more than those with 4.8% at the early stages of trafficking; however, as load applications were applied, the rutting of mix C1 plateaued while mix C2 surpassed the latter with a larger rutting slope. Mix C3 in both dry and wet state of testing had the largest rutting slope and had potential to keep increasing beyond the test's set loading applications, which indicates the severity of adding binder content above the design limit on the rutting susceptibility. The deteriorating rutting resistance when adding binder in excess could be attributed to the binder characteristic itself which tends to soften the overall mixture along with taking up volume from the aggregates that affects the strength of the mix. (Abu Abdo & Jung, 2016)

Table 8 Anova results for application 2

| | Factor | Rut Difference | P-value | Significance |
|---|---|---|---|---|
| **Dry** | C1-C2 | $3.8\% < 4.8\%$ | 0.0158 | ✓ |
| | C1-C3 | $3.8\% < 5.8\%$ | 1.08e-11 | |
| **Wet** | C1-C2 | $3.8\% < 4.8\%$ | 0.000901 | |
| | C1-C3 | $3.8\% < 5.8\%$ | 1.87e-13 | |
| **Dry-Wet Comparison** | C1-C1 | $3.8\%_{dry} < 3.8\%_{wet}$ | 7.748e-08 | |
| | C2-C2 | $4.8\%_{dry} < 4.8\%_{wet}$ | 2.238e-05 | |
| | C3-C3 | $5.8\%_{dry} < 5.8\%_{wet}$ | 2.861e-06 | |

Table 8 provides a statistical comparison of the samples in (1) dry conditions, (2) wet conditions, and (3) a comparison within the dry-wet rutting results of the samples – which all indicate that there is a significant statistical difference between all the tested asphalt briquettes and provides evidence that the change in binder content had an evidential role in affecting the rutting performance.

### *5.2.1. One-way ANOVA on Air Voids*

Permanent deformation is influenced by the extent of air voids that asphalt mixtures have due to densification; therefore, in order to diminish the effect of air voids and isolate the effect of the binder content variation – a one way ANOVA is conducted (table 9) on the asphalt briquettes to investigate whether there was an evidence of air voids on any of the samples' rutting behavior. Based on that, there was no evidence of effect of air voids on the rutting performance of the samples.

Table 9 One-way ANOVA on air voids and binder deviation (condition)

| APT Run | Factor | P-value |
|---|---|---|
| **Run 1: Dry** | Air voids | 0.738 |
| **Run 1: Wet** | Air voids | 0.861 |

### 5.3. Application 3: Analysis and Results

Figure 36 presents the air void percentage for the twenty-four fabricated samples against their respective rut depth. To investigate whether there is a statistical effect of air voids on the induced rut depth, a two-way Analysis of Variance (ANOVA) was conducted on the rut depth of each run with the conditions and air voids (table 12). In all APT runs, there was a statistically significant effect of the conditions, while the effect of air void percentage on the rut depth was statistically insignificant.

Table 10 One-way ANOVA on air void and conditions

| APT Run | Factors | P-value |
|---|---|---|
| **Run 1: Dry** | Air voids | 0.441 |
| | Conditions | 0.014 |
| **Run 1: Wet** | Air voids | 0.5979 |
| | Conditions | 0.0127 |
| **Run 2: Dry** | Air voids | 0.4024 |
| | Conditions | 0.0417 |
| **Run 2: Wet** | Air voids | 0.841 |
| | Conditions | 0.0112 |

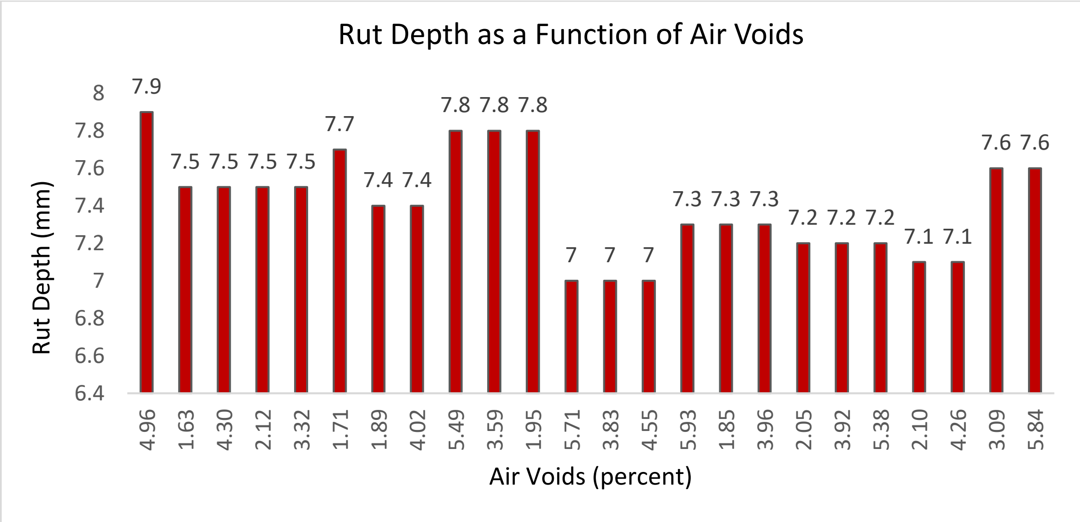

Figure 36 Air void percentage as a function of the respective rutting depth

### 5.4 Evaluation of Rut Potential

Two samples of each mix condition were tested for rutting potential in a dry and wet state at a temperature of $40 \pm 2°C$ for 11000 cycles and the rutting depths were recorded as a function of load repetitions. The rutting depth of each two samples of the same mix condition were averaged and plotted against all other mix conditions (figure 37). Each condition was numbered with either one or two corresponding to the state of testing, either one for dry, or two for wet.

Testing for rutting potential under dry conditions, the final rut depth between mixes using virgin binder rutted the most. As for mixtures using SBS-modified binder, asphalt briquettes exhibited the least amount of rut depth.

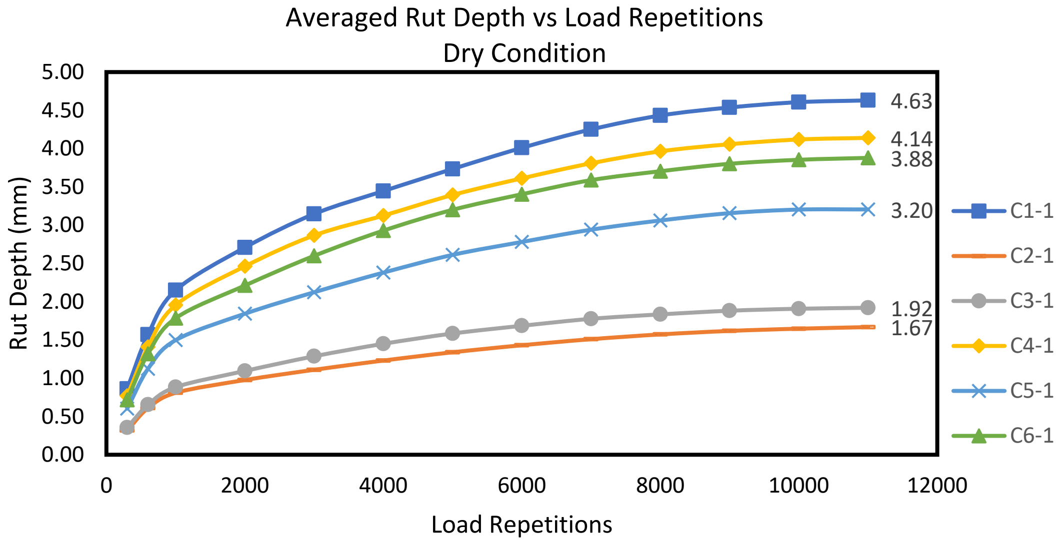


Figure 37 Average rut depth under dry conditions as a function of load cycles

### *5.4.1. Comparisons Within Different Mixes in a Dry State of Testing*

Figure 38 summarizes the comparative study conducted between the six conditions using Welch two-sample t-test with an assumed $\propto = 0.05$. The main objective of this comparative study is comparing two samples with the same conditions except one. By isolating the effect and performing statistical analysis, the evidence of effect, or the lack of it, can be captured.

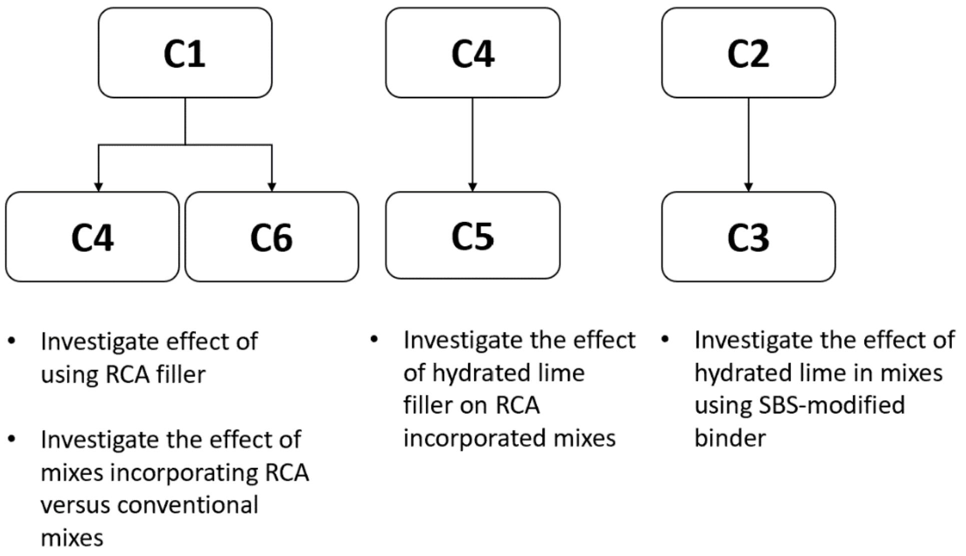


Figure 38 Comparative study plan between asphalt mixtures tested in dry condition

- The rutting difference between mixes C1 and C6 was marginally insignificant with C1 exhibiting a higher rut depth. This signifies that there is no evidence that RCA filler had a significant effect on the rutting potential of C6. However, if the assumed $\propto$ is less stringent, then C6 would be concluded was the better performing mix. As such, in terms of permanent deformation, this finding suggests that RCA filler could fully substitute the conventional limestone filler used in mixes while performing similarly or could outperform mixes with conventional filler. In both scenarios, RCA filler is a potential CDW material that could be utilized in asphalt pavements with promising results.
- Between C4 and C5, C4 had a higher induced rut than C5, and this difference was statistically significant for an $\propto = 0.05$ having a p-value of 0.04112. This alludes that there was an evidence of hydrated lime filler in decreasing the overall rut potential of mixes using non-modified binder.

- For mixes C1 and C4, no statistical difference was found between their rutting performance. Therefore, there is no evidence that RCA had any sort of effect on the rutting potential of mix C4 in dry state testing
- There was no statistical difference between the rutting values recorded for mixes C2 and C3. This suggests that there is no evidence of hydrated lime filler improving rutting resistance in mixes using SBS-modified binder.
- Comparing mixes C1 and C5, there was marginal statistical insignificance, meaning that if the assumed $\alpha$ was less stringent, there could be evidence that mixes with RCA aggregates and hydrated lime perform similarly, under dry conditions, to the control mix using limestone aggregates, filler and non-modified binder.

#### *5.4.2. Comparisons Between Mixes: Wet vs Dry State of Testing*

After obtaining the rutting values of the conditions tested under a dry state, the same mixes were tested in a wet state at $40 \pm 2°C$ after moisture conditioning and temperature stabilization for two hours. The rutting values are recorded throughout the $11000$ loading applications in figure 39, where mixes are denoted with their corresponding condition followed by two, for wet testing. A comparative study of the rutting values within the mixes was conducted, along with comparisons to their rutting performance under dry conditions.

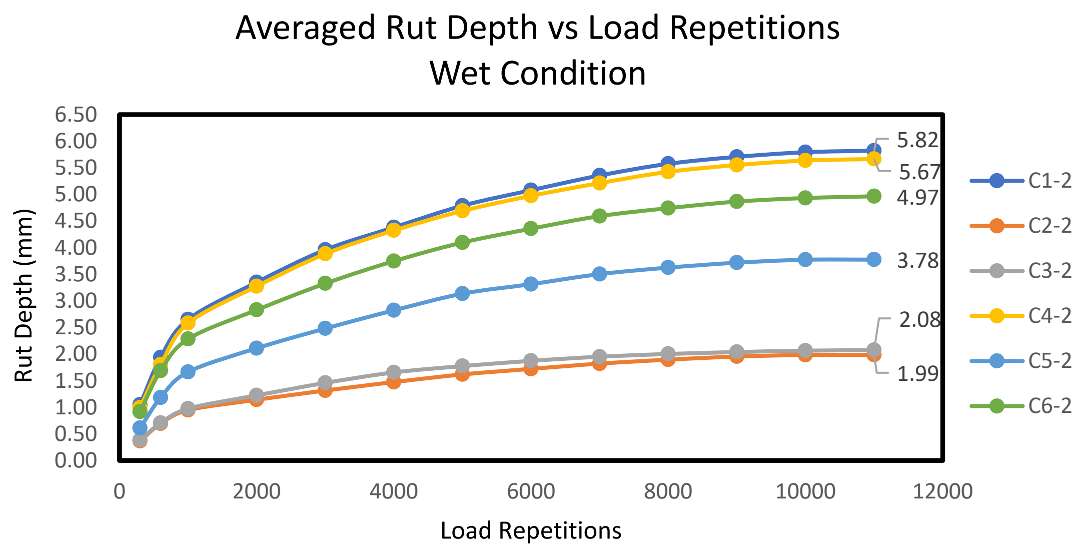


Figure 39 Average rut depth under wet conditions as a function of load cycles

The purpose for this is to assess the performance of the added components in each mix under moisture conditioning and consequently evaluate the moisture susceptibility exhibited for each mixture. The comparative process can be summarized in figure 40.

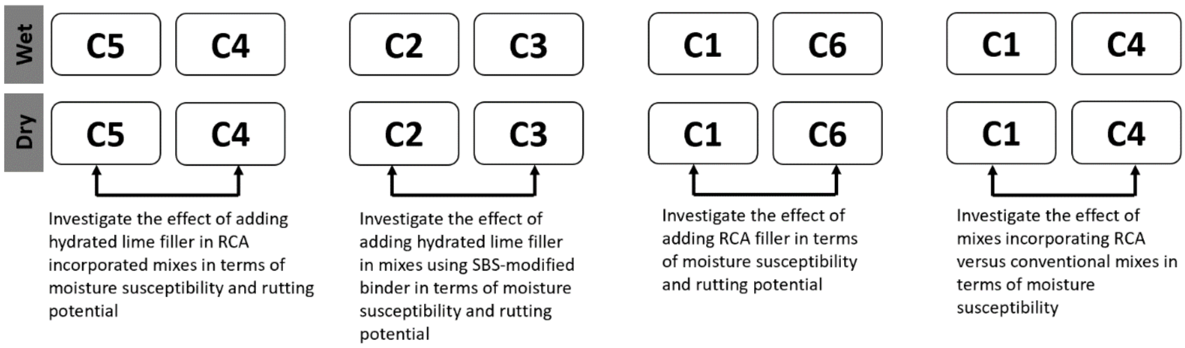


Figure 40 Comparative study plan between asphalt mixtures tested under wet condition

- The rutting values for mix C5 were statistically less than those of mix C4. This implies that there was evidence of hydrated lime filler in reducing the rut potential in mixes using non-modified binder tested in a wet state. Also, C5 mix, which had hydrated lime as a filler, had a final rut increase between dry and wet state testing of 18%. Along with C4 rutting more, the rut percent increase for the mix was 37%. As a result, it can be observed that there was a noticeable effect of hydrated lime in reducing the permanent deformation exacerbated by moisture damage.
- There was no statistical difference between the rut depth of mixes C2 and C3 when tested in a wet state. However, the rut increase for C2 was larger than C3, having values of 19% and 8%, respectively. Even though hydrated lime lessened the permanent deformation caused by moisture damage, the same mix had exhibited significantly more bleeding than mix C2 while testing under the APT. (figure 41)
- Similar to dry state testing, mixes C1 and C6 had no statistical difference in their rutting values. This concurs that, in wet state testing, there was no evidence of RCA filler affecting the rut potential of mix C6. The rut percent increase was also somewhat similar, with mix C1 increasing 26% in rut depth and C6 increasing 28%. This goes to show that, even with moisture conditioning, mixes incorporating RCA filler has the potential of performing similar to conventional mixes.
- Under wet testing, mix C5 performed statistically superior to mix C1. Thus, there is an evidence that adding RCA aggregates and hydrated lime in improving the rutting performance when compared to the control mixture.

- For mixes C4 and C1, there was no statistical difference in their recorded rut depth. Although the difference in rut wasn't significant, the rut percent increase varied between the two mixes. C1 had a rut increase of 26% while C4 had a rut increase of 37%. This could be due to the incorporation of RCA and its susceptibility to moisture damage.

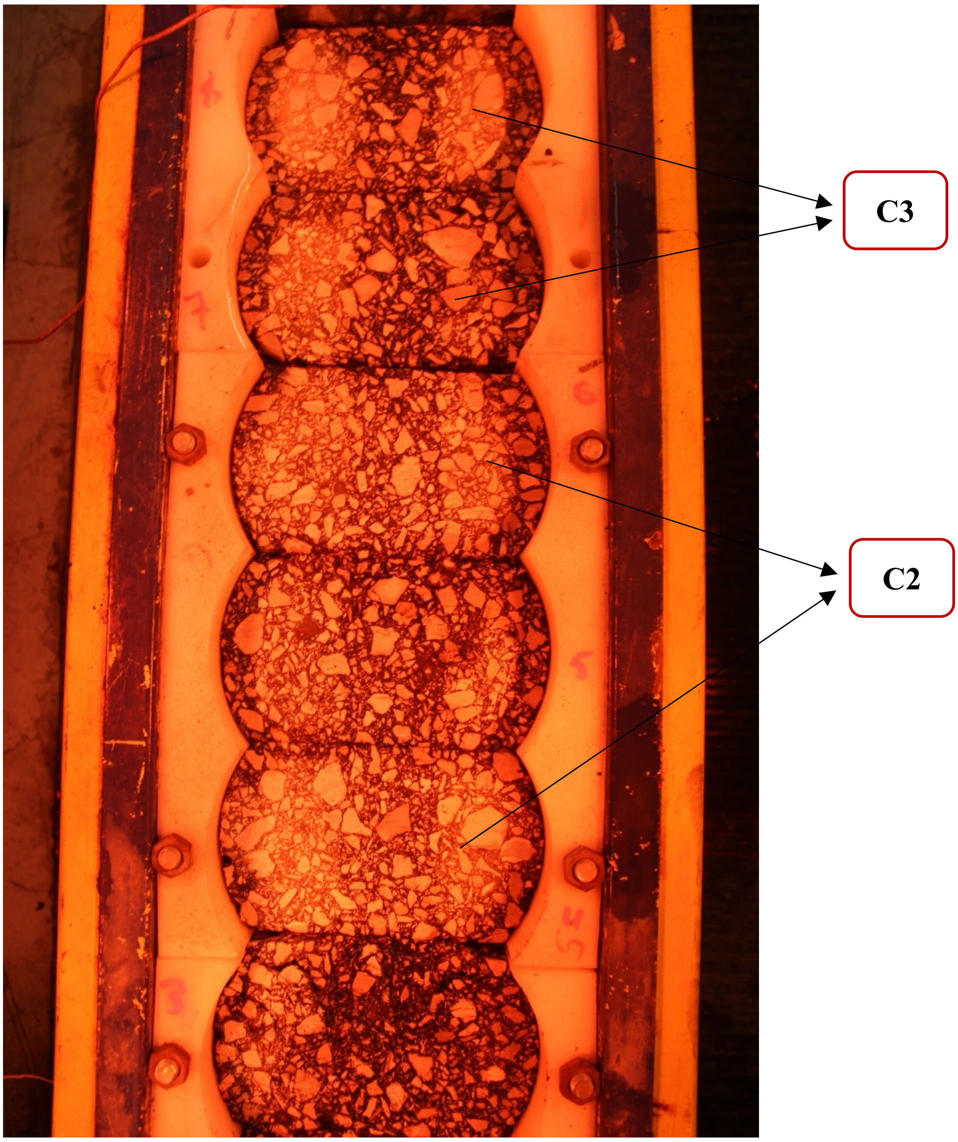


Figure 41 Test bed showcasing the excessive bleeding in mix C3

### *5.4.3. Rutting Exacerbation by Moisture Damage*

It is important to observe and study the rutting increase between samples tested in both dry and wet conditions and the extent of moisture induced damage exhibited by different conditions of asphalt mixtures.

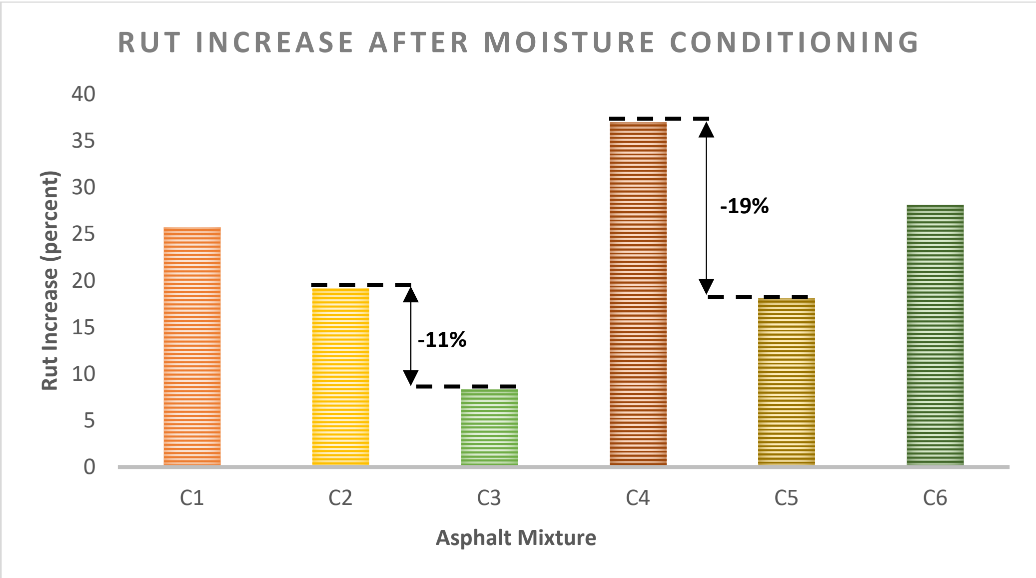


Figure 42 Rut increase after moisture conditioning for the different asphalt mixtures

Figure 42 presents the percentage of rut increase between dry and wet testing conditions for the asphalt mixtures included in this experimental plan. It is noticeable that for mixes C2 and C3; mixes C4 and C5, there was a significant effect of hydrated lime in lessening the extent of rut increase after moisture conditioning for mixtures using SBS-modified binder ($-11\%$) and RCA aggregates ($-19\%$). This exploration serves as further knowledge to the controversial set of studies tackling hydrated lime in asphalt pavement applications. As for RCA filler, the rut increase between the two testing conditions were statistically insignificant.

Table 11 Summary of the main outcomes of the experimental plan

| | Rut Depth | Bleeding | Moisture Susceptibility |
|---|---|---|---|
| **C1 – C6** | Statistically marginally insignificant | X | 26% - 28% |
| **C2 – C3** | Statistically insignificant | Exacerbated bleeding in C3 | 19% - 8% |
| **C1 – C4** | Statistically insignificant | X | 26% - 37% |
| **C4 – C5** | Statistically significant | X | 37% - 18% |
| **C1 – C5** | Statistically significant | X | 26% - 18% |

The main outcomes are summarized in table 13. To recap, mix C1 was the control mix, having limestone aggregates and filler, with virgin binder. C2 and C3 incorporated SBS-modified binder, while C3 utilizing hydrated lime filler. C4 and C5 both had 30% of their aggregates replaced by RCA, while C5 had hydrated lime as filler instead of limestone filler. Mix C6 had limestone aggregates, virgin binder, and RCA filler. For both dry and wet state of testing under the APT, results indicated that incorporating hydrated lime into asphalt mixtures, with and without RCA aggregates, could lessen the rutting susceptibility exacerbated by moisture damage; however, asphalt mixtures with SBS-modified binder and hydrated lime (C3) exhibited excessive bleeding during APT trafficking. In addition, asphalt mixtures using RCA mineral filler (C6) performed similarly, in terms of rutting and moisture susceptibility, to those with limestone filler – making RCA mineral filler potentially fully substituting limestone fillers in asphalt pavements.

Moreover, asphalt mixtures using RCA and hydrated lime (C5) had better rutting resistance when compared to the control mix (C1) and tested under wet conditions; that was not the case when comparing the control mix with asphalt mixtures using RCA (C4). There was a significant role for hydrated lime in supporting the rutting resistance for mix C5 by combating the moisture damage, which in return outperformed mix C1.

## 5.5. Establishing Performance-Based Pay Factors

The testing conducted in application two allowed for the detection of different rutting behaviors when the binder content deviated, as penalized by DOTs, by the upper and lower limit. As such, the performance exhibited by the samples adopting the suggested deviations in binder content and air voids percentage can be used in simulating the collective costs associated with such performance – which are under agency and user costs.

RealCost is a software developed by the FHWA to perform life-cycle cost analysis (LCCA) in compliance with the administration's best practices. The software takes into consideration all factors and their associated costs included in the construction, rehabilitation, and maintenance of asphalt pavement structures. Taking the rutting performance of the control sample as reference, the subsequent performance of other samples could relatively compare, in terms of the frequency and time delay/acceleration of required rehabilitations of the pavement. Consequently, the relative cost between the different alternatives can be established, followed by the pay factors.

### *5.5.1. Performance Metric: Air Voids*

The financial assessment of the evaluated alternatives due to deviations in air void percentage is presented in table 10.

Table 12 Deterministic results of the financial assessment of the proposed alternatives

| Total Cost | Alternative 1 | | Alternative 2 | | Alternative 3 | |
|---|---|---|---|---|---|---|
| | Agency Cost ($1000) | User Cost ($1000) | Agency Cost ($1000) | User Cost ($1000) | Agency Cost ($1000) | User Cost ($1000) |
| **Undiscounted Sum** | $3,000.00 | $862.28 | $6,000.00 | $1,724.56 | $7,200.00 | $2,069.47 |
| **Present Value** | $3,000.00 | $862.28 | $5,232.28 | $1,503.89 | $6,385.34 | $1,835.31 |
| **EUAC** | $201.65 | $57.96 | $351.69 | $101.09 | $429.19 | $123.36 |
| | | | | | | |
| **Lowest Present Value Agency Cost** | **Alternative 1** | | | | | |
| **Lowest Present Value User Cost** | **Alternative 1** | | | | | |

The construction quality – influenced by the degree of compaction – is monetized; such that superior construction quality would lead to less frequent, costly rehabilitation procedures. Meanwhile, inferior construction practices, which could be associated to unsatisfactory compaction procedures by the contractor, could lead to additional, more costly, rehabilitations. From that rationale, the reference scenario is alternative one, which corresponds to adequate compaction till 4%. Consequently, the relative performance of the other inferior alternatives could be associated with a pay factor that is dependent on a performance metric, in this case, permanent deformation. Alternative two pay factor takes the following form

$$Equation\ 3: \frac{(agency+user\ cost)_{alternative1}}{(agency+user\ cost)_{alternative2}} = \frac{3{,}862.28}{6{,}735} = 0.573$$

Equation 3: Pay factor calculation based on relative performance

As for alternative three, which assumes a poor compaction degree, a pay factor of 0.469 is recommended.

It is worth noting that pay factors that are based on performance metrics computed in this method are similar to those suggested by most DOTs. For example, the state of Florida's standard specification for road construction, section governing asphalt pavement protocols, the pay factor for a lot could decrease as low as 0.55 for air voids deviation greater than 2.5%; which is in agreement with the proposed method in this study.

### *5.5.2. Performance Metric: Binder Content*

The deterministic results of the financial assessment of the three alternatives, performed on RealCost, are summarized in table 11.

Table 13 Deterministic results of the financial assessment of the proposed alternatives

| Total Cost | Total Cost | | | | | |
|---|---|---|---|---|---|---|
| | Alternative 1 | | Alternative 2 | | Alternative 3 | |
| | Agency Cost ($1000) | User Cost ($1000) | Agency Cost ($1000) | User Cost ($1000) | Agency Cost ($1000) | User Cost ($1000) |
| **Undiscounted Sum** | $5,000.00 | $742.99 | $4,500.00 | $371.49 | $8,750.00 | $1,114.48 |
| **Present Value** | $4,616.14 | $647.92 | $4,500.00 | $371.49 | $7,991.17 | $994.82 |
| **EUAC** | $310.28 | $43.55 | $235.25 | $24.97 | $537.13 | $66.87 |
| **Lowest Present Value Agency Cost** | | | Alternative 2 | | | |
| **Lowest Present Value User Cost** | | | Alternative 2 | | | |

In the case of binder content, three alternatives were explored: (1) standard performance for the control mix (alternative 1) and (2) substandard performance due deviation in the binder content (alternative 2,3). For alternative one, the binder content was set as obtained from the mix design, and the rutting performance under the APT was taken as reference to construct relative performances for the other two alternatives.

As for alternative 2, the expenditure scenario was simulated for a pavement structure that has a negative binder deviation. The consequent pay factor is 1.08, which typically indicates a surplus in payment due to superior construction outcome and quality control measures, according to the standard specifications of Florida, Texas and other states. However, this is not the case by following this method in obtaining pay factors. While a deficit in binder content may reduce permanent deformation (Abu Abdo & Jung, 2016), it also leads to implications in other performance metrics. For example, the fatigue life of the asphalt pavement could be adversely impacted – along with early and excessive amounts of cracking in the pavement structure (Tavakol et al. 2018). Since this study is only accounting for rutting as the performance metric in evaluating performance-based pay factors, it may be misleading when cases like this arise; therefore, it is of importance to also include and combine other performance metrics in future studies.

On the other hand, the performance of asphalt mixtures which possess binder content in excess is translated into monetary values by adjusting the construction and rehabilitation practices accordingly. A pay factor of 0.585 – closely related to the penalties set by different DOTs (Florida, Texas, Illinois) – is a reasonable penalty that emphasizes and stresses on an adequate performance rather than numerical and empirical control limits.

# CHAPTER 6

# CONCLUSION AND RECOMMENDATIONS

This study explored the utilization of accelerated pavement testing on two fronts: (1) evaluating the pay factors set by different DOTs and establishing performance-based pay factors using performance metrics and (2) investigate the rutting and moisture susceptibility of different asphalt mixtures. The following conclusions were drawn:

1. The presented methodology in establishing pay factors based on performance metrics extracted from accelerated pavement testing yielded reasonable pay factors that emphasize on the performance of asphalt structures rather than volumetric control limits that is typically used by standard specifications for construction for different states. The resulting pay factors correlated well with the values proposed by the agencies. However, there are limitations to this methodology. When computing pay factors for cases when the binder content deviation is in deficit, the rutting performance is similar to the case of normal construction, or even superior. This yields a pay factor that is equivalent to 1 or greater, which is not the case. The deficit in binder content, although does not adversely affect rutting, it has severe implications on the fatigue life of asphalt pavements – which is not translated into the resulting pay factor that is based on rutting performance model. Therefore, other performance metrics could be integrated to present more comprehensive outputs.

2. The APT is capable of testing multiple asphalt mixtures under different loading configurations and temperatures and produces repeatable results – making the assembled APT a reliable, economical and a practical testing method for advanced evaluation of asphalt mixtures.
3. The usage of RCA alone increases the moisture damage but does not affect the rutting susceptibility of asphalt mixtures compared to the control mixture; however – under wet conditions – incorporating hydrated lime into asphalt mixtures using RCA lessens the rutting exacerbated by moisture damage due to lime's mode of action and surpasses the performance of the control mix. This finding sets the tone for future utilization of construction and demolition waste, with hydrated lime into asphalt pavement applications.
4. Although hydrated lime had an effect in improving moisture resistance, mixtures with SBS-modified binder and lime displayed excessive bleeding.
5. Asphalt mixtures with RCA mineral filler performed similarly in terms of rutting and moisture susceptibility; consequently, making RCA mineral filler as an adequate replacement to limestone filler.
6. The binder type used in this study, SBS-modified and virgin binder, had different behavior with hydrated lime. Asphalt mixtures using virgin binder and SBS-modified binder had different decrease in the rut increase between dry and wet testing, having values of $12\%\ and\ 8\%$, respectively.

# CHAPTER 7

# FUTURE RESEARCH

According to the testing program and experimental work conducted in this study, there is a need for future follow-up research. The recommended research tackles the following:

1. Based on the methodology followed for pay factors in this study, future research could develop a supplementary approach to account for different performance models, such as fatigue life in the computation of pay factors that account simultaneously for more performance metrics – achieving improved representation of asphalt pavement performance and cost simulation
2. Investigate different proportions of coarse RCA as percentage of the total aggregates in asphalt mixtures and their behavior with hydrated lime in terms of rutting and moisture susceptibility.
3. Evaluate different asphalt mixtures that explore other combinations and types of aggregate, binder, and filler types.
4. Investigate the phenomena of excessive bleeding in asphalt mixtures incorporating SBS-modified binder and hydrated lime on a chemical level.

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