Best Practices in Measuring Rutting and Shoving on Asphalt Pavements

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Abstract

The Superpave mix design method developed by the Strategic Highway Research Program (SHRP) was implemented to create a mix design system, performance-based asphalt binder specifications, and performance-based asphalt mix specifications. SHRP found success with the implementation of the first and second objectives. However, the third objective, i.e. performance-based asphalt mix specifications, was not implemented successfully due to some complexities. Since highway agencies have only been using mix design and asphalt binder specifications to capture the rutting susceptibility of asphalt pavements, there is a lack of the appropriate performance testing needed to investigate the rutting performance of asphalt mixtures. Due to the continuous increase in heavy truck traffic, municipalities such as the Regional Municipality of York in Ontario are experiencing excessive rutting in most of their intersections. It is essential that agencies implement appropriate performance testing methods and a threshold on rutting to help specify high rut resistance mixtures during the tendering process. The purpose of this paper is to provide state of the art testing methods for an asphalt mixture's suitability to rutting and shoving. This paper further evaluates the practicality of these test methods when compared to the asphalt mixtures primarily used in Ontario.

Introduction

Pavement deformation, or rutting, as shown in Figure 1, is one of the most serious asphalt pavement distresses. It manifests itself as surface depression in wheel paths, especially in areas exposed to heavy traffic loading, static loading, and frequent vehicle braking and accelerating such as bus stops and approach intersections. Rutting has a significant impact on the road safety. As asphalt concrete is an impervious material, the rutted areas trap water and cause hydroplaning which reduces the surface layer friction. In addition, deeper ruts make vehicle handling challenging which in turn makes driving hazardous to users (Al-Mosawe, 2016). Therefore, it is crucial to predict and determine the rutting susceptibility of an asphalt mixture.

Figure 1: Rutting in Approach Intersection at Heavy Truck Traffic Road in York Region

There are two main forms of rutting. The first type is the rutting that occurs due to deformation in the subgrade or underlying layers such as base or sub-base which is identified as a structural rutting failure (Asphalt Institute, 2014). In this type of rutting, the pavement structure as a whole is deformed, as shown in Figure 2 (Asphalt Institute, 2014). The second type of rutting is due to inadequate asphalt concrete mixture stability. In this scenario, the asphalt concrete mixture has low shear strength which results in the accumulation of unrecoverable strain resulting from applied wheel loads (Faruk et al., 2015). This results in the densification and/or lateral movement of the asphalt concrete layer under traffic, as shown in Figure 3. The focus of this paper is on the rutting which occurs on the asphalt surface layer due to asphalt concrete mixture's inadequate shear strength.

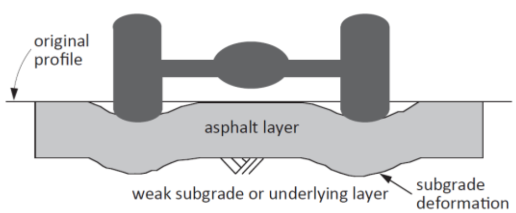

Figure 2: Rutting from Weak Subgrade (Asphalt Institute, 2014)

Rutting can occur in three (3) different stages, as shown in Figure 4, namely: decelerating (primary), stationary (secondary), and accelerating (tertiary) stages. In the primary stage, the accumulated permanent strain increases rapidly and the strain rate drops. In this stage, densification generally occurs. As indicated by many researchers, the initial deformation usually occurs in the first or two years of a pavement's service life which could be due to inadequate compaction during construction (Said,et al., 2016). Typically, roads with higher air voids are susceptible to higher densification related rutting (Du et.al, 2018).

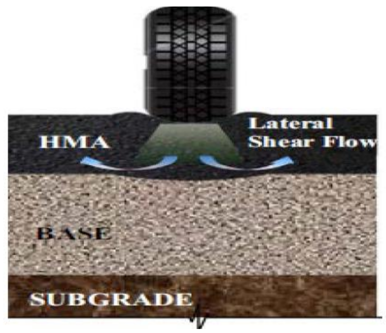

Figure 3: Rutting from Inadequate Mix Stability (Faruk et al., 2015)

The most critical rutting stage in asphalt concrete pavement is lateral plastic flow deformation, or "shear-related deformation," which is a result of an inability to resist the shear stresses imparted from frequent repetitions of heavy axle vehicles, braking, and turning (Du et.al, 2018).

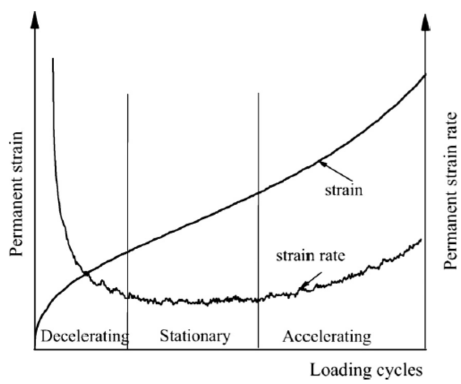

Figure 4: Permanent Strain vs. Loading Cycles (Witczak, 2002)

Asphalt Mixture Design

The main purpose of asphalt mixture design is to determine the most economical proportions of aggregate, asphalt binder, additives, and optional supplementary materials needed to prevent pavement distresses such as rutting which significantly influences the in-service performance of asphalt pavements.

Asphalt mixtures must be designed, produced, laid down, and compacted such that the durability and stability of the mix are met during the pavement's service life. Asphalt mixture durability is defined as the characteristic that determines how well an asphalt pavement can preserve its structural integrity while exposed to climate and traffic loading, thus resulting in maintaining the same satisfactory level of service throughout its service life (Bonaquist, 2014). On the other hand, the stability of an asphalt mixture refers to the resistance required to prevent permanent deformation in asphalt pavements under the stresses of traffic loading and high temperatures (Asphalt Institute, 2014).

The Superpave mix design method developed by the Strategic Highway Research Program (SHRP) from 1987 to 1993 was designed to be the most appropriate asphalt mixture design method compared to its preceding methods, i.e. Hveem and Marshall. The significant objectives of SHRP were to develop and implement a mixture design system, performance-based asphalt binder specifications, and performance-based asphalt mixture specifications. SHRP was successful with the implementation of the first and the second objectives. However, the third objective, i.e. performance-based asphalt mixture specifications, was not implemented successfully due to some complexities. As a result, the Superpave mixture design system did not provide a simple test to measure the stability of asphalt mixtures as Hveem and Marshall methods provided (Huber, 2017). Therefore, Departments of Transportation (DOTs) in the US and Canada only practiced mixture design and asphalt binder specifications that applied to the construction of asphalt pavements. The lack of implementation of appropriate performance-based asphalt mixture specifications have placed the Superpave mixture design at the same level of effectiveness as the previous mixture design methods, Hveem and Marshall, due to being unable to predict and measure the expected asphalt pavement performance against distresses such as rutting. Furthermore, according to the Superpave mixture design method, proportioning of the aggregate and asphalt binder in a mixture design is dependent on two components of the mixture design: the aggregate and asphalt binder's characteristics and the mixture's volumetric properties such as air voids, voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA).

Pavement distresses such as rutting has proved that the recipe and volumetric approach used in Superpave may not be necessarily capturing the short-term and long-term durability of the asphalt mixture, as well as not providing insight into rutting and shear resistance. Moreover, the Superpave mix design method is not effective enough to predict the potential behavior of asphalt pavements in the field and the aforementioned shortcomings gradually began to become more complicated with the introduction of Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS), warm-mix asphalt additives, rejuvenators, polymers, and fibers into asphalt mixtures (NCHRP 9-57, 2016).Therefore, it is crucial to introduce testing that can capture an asphalt mixture's durability and increases the level of reliability associated with the level of resistance to rutting and shear (NCHRP 9-57, 2016).

In addition, these performance tests could be done as part of either performance-verified volumetric design or performance-modified volumetric design, targeting asphalt mixture durability. In performance-verified volumetric design, performance tests are conducted to verify the resistance to a specific distress in asphalt mixture such as rutting. In performance-modified volumetric design, on the other hand, performance tests are conducted to adjust the asphalt mixture's proportions to resist rutting such as adjusting the asphalt concrete content.

Factors Affecting Rutting

Factors such as asphalt binder, the aggregate's physical properties and skeleton, temperature, air voids (%), traffic load, and traffic speed are some of the factors affecting an asphalt mixture's shear strength.

Asphalt Binder

Based on the studies by Sybilski et al, asphalt binder can be attributed to as much as 40% of the rutting resistance of asphalt mixtures (Sybilski et al., 2013). Asphalt binder is a viscoelastic material that behaves as an elastic material at lower temperatures while at higher temperatures it behaves more like a viscous fluid as presented in Figure 5 (FHWA, 2000). In addition, when the asphalt binder is subjected to loading, it deforms. However, the portion of the deformation which recovers as the load is removed shows both the elastic behaviour of the binder and the portion of the deformation which is unrecoverable (permanent), which is referred to as plastic behaviour (Baghaee Moghaddam, 2019). Temperature plays an important role as asphalt becomes more susceptible to deformation as it becomes less viscous and soft at high temperature. As a result, it is important to improve the rheological properties of asphalt binders at high temperatures, such as increasing the stiffness to improve the resistivity of the asphalt mixture to shear failure induced by repetitive loading at high temperatures (Sybilski et al., 2013).

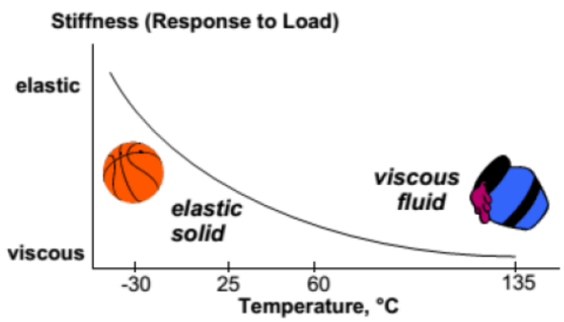

Figure 5: Viscoelastic Behavior of Asphalt Binder (FHWA, 2000)

There will be a higher frequency and longer duration of heat waves in the future (Intergovernmental Panel on Climate Change, 2014). These changes in weather trends, especially the changes in temperature, will have a negative impact on transportation infrastructure pavement as it reduces its longevity (Environment Canada, 2007). As a result, it is important to understand the impact of temperature on asphalt mixtures.

Superpave mixture design has introduced an asphalt-grading system called Performance Grading (PG) with the intention of matching the physical binder's properties to the desired levels of resistance to rutting, fatigue, and low-temperature cracking, subject to local climate and environmental conditions (Varamini, 2016). In areas such as intersections that experience high equivalent single axle loading (ESALs) in addition to slow moving traffic, additional shifts in the selected high-performance grade asphalt binder's—known as "grade-bumping" need to be implemented in order to avoid permanent deformation, as shown in Table 1.

Table 1: Superpave Grade-Bumping Chart (NRC, 2003)

Design ESALs million	High Temperature Grade Increase in 6°C Grade Equivalents		
	Heavy Traffic (Trucks and/or Buses) Loading Rate (Speed)		
	Standing < 20 km/hr	Slow 20 to 70 km/hr	Standard > 70 k,/hr
< 0.3	–	–	–
0.3 – < 3	2	1	–
3 – 10	2	1	–
10 – < 30	2	1	–
≥ 30	2	1	1

To capture the shear resistivity of asphalt binder, the Superpave mixture design method introduced the dynamic shear rheometer (DSR) test. This test measures the complex shear modulus ($G*$) and phase angle (δ) of the asphalt binder, the most important parameters to provide information about the rheological properties of asphalt binders during the shearing process. The complex shear modulus ($G*$) can be considered the sample's total resistance to deformation when sheared, while the phase angle (δ) is the lag between the applied shear stress and the resulting shear strain (PI,2021). $G*/\sin\delta$ is also known as the rutting parameter (PI, 2021). However, the studies indicated that the $G*/\sin\delta$ targeted value calculated by the DSR test in the Superpave mixture design is not a good representative of what occurs in the field since the results are based on one cycle which only considers the linear visco-elastic region. More recently, the Multiple Stress Creep Recovery (MSCR) test was introduced to better simulate rutting as multiple cycles applied to the binder better demonstrates rutting as a non-linear failure. The MSCR test investigates the creep recovery behaviour of asphalt binder by considering two parameters: non-recoverable compliance (J_{nr}) and percent recovery (R). A prescribed stress is applied for 1 second and then removed (rest period) for 9 seconds for a total of 10 creep/recovery cycles. This is repeated for a number of cycles and the residual strain after the last load application is recorded (Du et al., 2018). The MSCR test is a better test method compared to DSR because it presents what occurs in an actual pavement since higher levels of stress and strain are applied to the binder during the test (Witzak, 2005). According to the study conducted by the Federal Highway Administrative (FHWA) at its Accolated Loading Facility (ALF), the J_{nr} parameter from the MSCR test provides an excellent correlation with rutting (FHWA, 2011).

Aggregate

Aggregate in asphalt mixtures also plays an important role in the shear strength of an asphalt mixture. The relationship between shear strength (τ_f), cohesion of binder (C), and the internal friction ($\sigma\tan\varphi$) can be expressed by the Mohr–Coulomb failure theory (Du et.al, 2018).

$$\tau_f = C + \sigma\tan\varphi \qquad (1)$$

According to the above equation, an increase in the cohesion of the binder and the internal friction angle of aggregate would enhance the shear strength of an asphalt mixture and its resistivity to rutting (Du et.al, 2018). Since aggregate has relatively little cohesion, its shear strength is primarily dependent on the resistance to movement or inter-particle friction provided by the aggregates (Asphalt Institute, 2014). Therefore, it is important to use angular and rough-textured aggregates to achieve higher aggregate interlock, leading to a rut resistant mixture as shown in Figure 6 (Asphalt Institute, 2014).

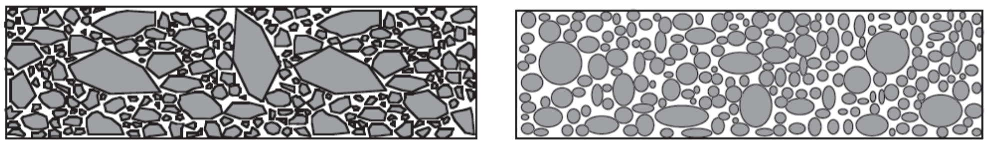

Figure 6: Aggregate Stone Skeleton (Asphalt Institute, 2014)

Superpave mixture design has provided limits and requirements on aggregate properties such as toughness, soundness, deleterious materials, coarse and fine aggregate angularity, and flat and elongated particles to provide rutting resistance for asphalt mixtures. These aggregate properties are categorized as consensus properties and source properties and are varied depending on traffic in terms of equivalent single axle loads, as shown in Tables 2 and 3 (Asphalt Institute, 2014).

Table 2: Aggregate Consensus Property Requirements (Asphalt Institute, 2014)

Design ESALs (In Millions)	Coarse Aggregate Angularity (CAA) (Percent), minimum		Uncompacted Void Content of Fine Aggregate Angularity (FAA) (Percent), minimum		Sand Equivalent (SE) (Percent), minimum	Flat and Elongated (F&E) (Percent), maximum
	≤ 100 mm	> 100 mm	≤ 100 mm	> 100 mm		
< 0.3	55/–	–/–	–	–	40	–
0.3 to < 3	75/–	50/–	40	40	40	10
3 to < 10	85/80	60/–	45	40	45	10
10 to < 30	95/90	80/75	45	40	45	10
≥ 30	100/100	100/100	45	45	50	10

Table 3: Recommended Superpave Source Property Tests and Typical Requirements (Asphalt Institute, 2014)

20-Year Design Equivalent Single Axle Loads (ESALs in millions)	Los Angeles Abrasion (Max. %) AASHTO T 96	Sodium or Magnesium Sulfate Soundness (Max. %) AASHTO T 104	Deleterious materials*	
			Clay Lumps/ Friable Particles AASHTO T 112	Lightweight Particles AASHTO T 113
< 0.3	45	25	<5	<5
0.3 to < 3	40	20	<4	<4
3 to < 10	30	15	<3	<3
10 to < 30	30	15	<2	<2
≥ 30	25	<10	<1	<1
*Specific tests and property requirements to be determined locally				

In addition to binder and aggregate properties, air void content (%) also has an impact on the durability of pavement in terms of rutting. A certain percentage of air voids is required in the volumetric design of the asphalt mixture to allow for asphalt expansion due to temperature increases and additional compaction under traffic (Asphalt Institute, 2014).

Performance Tests for Evaluating Rutting in an Asphalt Mixture

As mentioned earlier, the lack of implementation of appropriate performance-based asphalt mixture specifications needed to capture the interaction between binder and aggregate and its effect on rutting has meant that the Superpave mixture design is unable to predict and measure the expected asphalt pavement performance against rutting. In addition, it is evident that recipe-based and volumetric asphalt mixture design alone lack an understanding of rutting and shear resistance in asphalt mixtures. Therefore, if projects mandate durability against rutting and higher reliability for the asphalt mixture, then some performance tests need to be introduced.

The tests that are introduced in this paper should capture the asphalt mixture's durability at higher temperatures and increase the level of reliability. These tests are used to better understand the performance of volumetric designs when tested at extremely high temperatures. The majority of these test methods are qualitative and are meant to provide an indexed performance threshold. Generally speaking, testing can be categorized into three testing types. For the purpose of this paper we are categorizing them into monotonic, dynamic, and simulative types of loading. In addition, some tests could be performed under dynamic or monotonic loading modes.

Simulative Test

Simulative tests are relatively simple tests that simulate the effect of traffic on a pavement sample by tracking a wheel load on asphalt mixtures, measuring the accumulated deformation per wheel load cycle as shown in Figure 7. This type of test provides an understanding of the mixture's performance in different stages such as those presented in Figure 7. These tests provide three different stages: decelerating (primary), stationary (secondary), and accelerating (tertiary) stages. In the last stage, a small number of load repetitions can cause a large amount of plastic deformation

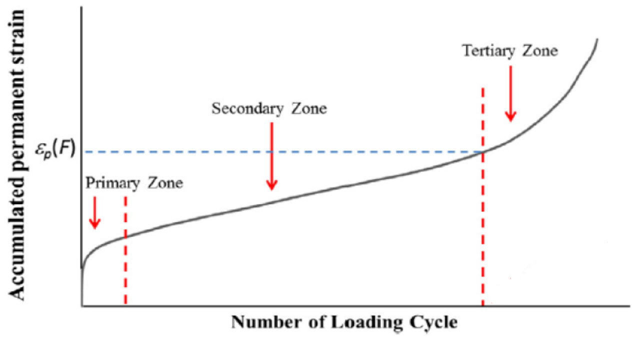

Figure 7: Typical Plot of Simulative Test Results (Zhang et al., 2013)

Hamburg Wheel Tracking Test (HWTT)

The Hamburg Wheel Tracking Device (HWTD), as shown in Figure 8, is used to evaluate the rutting resistance of asphalt mixtures. In addition, it could be used to evaluate the moisture susceptibility of compacted asphalt mixtures specimens that are submerged in water (Brown et al., 2009, p.318). This test is performed in accordance with AASHTO T324 "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)" (AASHTO, 2016). The device tracks a 158 lb (705 N) load steel/rubber wheel across the surface of a cylindrical specimen 150 mm in diameter and 62 mm high that is submerged in a hot water bath at 50°C (Brown et al., 2009, p.318). To determine the rut resistivity of the asphalt mixture, the accumulated permanent deformation is typically measured after the machine has applied 20,000 wheel passes. Table 4 shows the minimum acceptable rut depth criteria associated with the number of wheel passes for different binder/asphalt mixture types in different state DOTs (Brown et al., 2009, p.320). The photo of specimens' condition before and after the test is presented in Figure 9. During the test, the deformations of specimens are recorded as a function of the number of passes. The moisture susceptibility is then evaluated by computing the stripping inflection point, defined as the intersection of the slopes of stripping and rutting as shown in Figure 10 (Brown et al., 2009, p.319).

Figure 8: Hamburg Wheel Track Device (Bashir et al., 2020)

Figure 9: Test Specimens Condition Before and After the HWTD Test

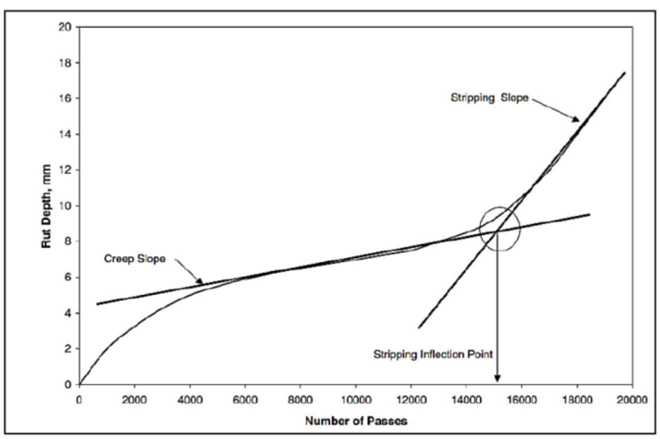

Figure 10: Typical results from Hamburg Wheel Tracking Test (NCHRP, 2011)

Table 4: HWTT Criteria Used by Different State DOTs (NCHRP, 20-07, 2018)

States	Binder/Mixture Type	Criteria
California	PG 58-xx PG 64-xx PG 70-xx PG 76-xx	Min. 10,000 passes at 12.5 mm rut depth Min. 15,000 passes at 12.5 mm rut depth Min. 20,000 passes at 12.5 mm rut depth Min. 25,000 passes at 12.5 mm rut depth
Colorado	All	Max. 4.0 mm rut depth at 10,000 passes
Iowa	All	Max. 8.0 mm rut depth at 8,000 passes Min. 10,000 or 14,000 passes with no SIP
Illinois	PG 58-xx (or lower) PG 64-xx PG 70-xx PG 76-xx (or higher)	Max. 12.5 mm rut depth at 5,000 passes Max. 12.5 mm rut depth at 7,500 passes Max. 12.5 mm rut depth at 15,000 passes Max. 12.5 mm rut depth at 20,000 passes
Louisiana	Level 1 high traffic Level 2 medium/low traffic	Max. 6.0 mm rut depth at 20,000 passes Max. 10.0 mm rut depth at 20,000 passes
Maine	All	Max. 12.5 mm rut depth at 20,000 passes Min. 15,000 passes with no SIP
Massachusetts	All	Max. 12.5 mm rut depth at 20,000 passes Min. 15,000 passes with no SIP
Montana	All	Max. 13.0 mm rut depth at 15,000 passes
Oklahoma	PG 64-xx PG 70-xx PG 76-xx	Min. 10,000 passes at 12.5 mm rut depth Min. 15,000 passes at 12.5 mm rut depth Min. 20,000 passes at 12.5 mm rut depth
Texas	PG 64-xx PG 70-xx PG 76-xx	Min. 10,000 passes at 12.5 mm rut depth Min. 15,000 passes at 12.5 mm rut depth Min. 20,000 passes at 12.5 mm rut depth
Utah	N_{design} > 75	Max. 10.0 mm rut depth at 20,000 passes
Washington	All	Max. 10.0 mm rut depth at 15,000 passes

As indicated in Table 4, some State DOTs have specified a different number of passes for different high temperature PG grades as the 50°C HWTD test temperature might be too excessive for some mixtures.

Asphalt Pavement Analyzer (APA)

The Asphalt Pavement Analyzer (APA) test measures the rut susceptibility of asphalt mixtures by running repetitive wheel load passes over beam-shaped or cylindrical specimens as shown in Figure 11 (Brown et al., 2009, p.315). The test is conducted according to AASHTO T340 "Standard Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)" and measures the permanent deformation of the test samples at the specified number of cycles. Typically, six cylindrical or three beam samples could be tested simultaneously by applying a wheel load and hose pressure of 100 lbf and 100 psi, respectively (Brown et al., 2009, p.317). The cylindrical specimens are 150 mm in dimeters and 75 mm tall. The APA test runs for 8,000 cycles and could be conducted at different temperatures, typically between 40 to 64°C, depending on the high temperature of the standard Superpave PG binder grade (Brown et al., 2009, p.317).

Figure 11: Asphalt Pavement Analyzer (NCHRP 20-07/Task 406, 2018)

French Rutting Tester (FRT)

The Laboratoire Central des Ponts et Chaussées (LCPC) wheel tracker, also known as the French Rutting Tester, shown in Figure 12, has been used to determine the susceptibility of asphalt mixtures to rutting. The FLR is an integral part of the LC26-410 method created by the Quebec Ministry of Transportation (MTQ) (Uzarowski et al., 2004). This device tracks a 5,000 N load tire which is inflated to 600 kPa across the surface of the slab specimens (180 wide x 500 long x 20-100 mm high) for 30,000 cycles (Cooley et al., 2000). The test is typically done at 60°C but the chamber can be set to any temperature between 35 and 64°C. The rutting depths are measured after 100, 300, 1,000, 3,000, 10,000, and 30,000 cycles and it is reported as a percentage of the slab thickness (Aschenbrener, 1992).

Figure 12: French Rutting Tester (Uzarowski et al., 2004)

Dynamic Test

In dynamic loading mode, a number of sinusoidal loading cycles are applied on the asphalt mixture specimen. The results can then be translated to deformation. The test results present the level of resistance of an asphalt mixture to rutting and shear as shown in Figure 13.

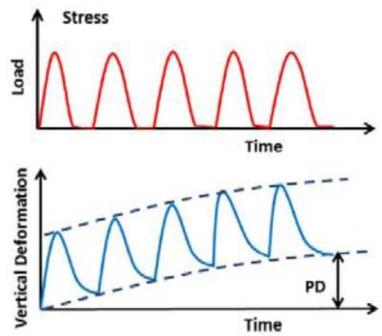

Figure 13: Typical Plot of Cyclic Test Results (Zhang et al., 2013)

Dynamic Modulus and Flow Number (FN) Test

The Dynamic Modulus test provides the stiffness of compacted asphalt mixture. The test is used to determine the dynamic modulus (|E*|) of specimens. The test is conducted in accordance with AASHTO T340 "Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA)" which involves applying a compressive load to a cylindrical specimen 100 mm in diameter and 150 mm high which can perform at different loading frequencies at different testing temperature. To capture rutting susceptibility, Varamini suggested that the test to be conducted at high temperature of 54.4°C and low frequency of 0.1 Hz (Varamini, 2016). Since the dynamic modulus test is a non-destructive test, the same sample could be used for the Flow Number Test.

The repeated load permanent deformation test, or Flow Number (FN) test, developed by NCHRP9-19 has shown a very high confidence in accurately predicting the rutting responses of asphalt concrete mixtures (Zhang et al., 2013). The FN test is conducted according to the AASHTO T 378 at repeated compressive loading cycles with each cycle consisting of 0.1 seconds loading time and 0.9 seconds resting time to measure vertical accumulated permanent strains as a function of loading cycles as shown in Figure 14 (Zhang et al., 2013). The test involves applying a compressive load to a cylindrical specimen 100 mm in diameter and 150 mm high which can perform at the testing temperature corresponding to the high PG grade. The load is repeated up to 10,000 cycles or until the specimens fails. As discussed earlier, when studying accumulated permanent strain versus the number of loading cycles, there are three stages or zones: primary, secondary, and tertiary zone (Zhang et al., 2013). The point at which the asphalt concrete mix reaches the tertiary zone is called the Flow Number which represents the number of load cycles at which any cycle beyond this point would cause lateral plastic flow with an increased deformation rate (Zhang et al., 2013).

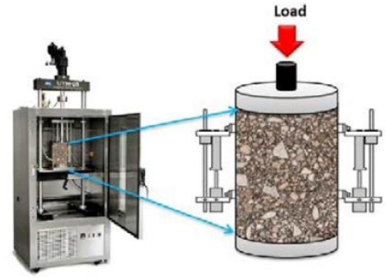

Figure 14: Test Setup and Configuration (Zhang et al., 2013)

Superpave Shear Tester (SST)

The Superpave Shear Tester shown in Figure 15 was developed as part of SHRP research to capture the shear resistivity of an asphalt mixture. The SST applies a biaxial load using a dual actuator feature (Brown et al., 2009): one actuator applies the vertical axial load and the other horizontal actuator moves the shear table that applies shear loads to cylindrical specimens 150 mm in diameter and 50 mm high with test temperatures ranging from 0 to 70°C (Brown et al., 2009). The SST test standard for sample preparation and testing procedure is presented in AASHTO T320 "Standard Method of Test for Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST)". The SST can be used to perform three different tests: a frequency sweep at constant height (FSCH) test, a repeated shear at constant height (RSCH) test, and a simple shear at constant height (SSCH) test. The FSCH, RSCH, and SSCH tests provide information in terms of stiffness, shear deformation, and rutting susceptibility, respectively.

In the RSCH test, a repeated haversine shear stress of 69 kPa is applied to an asphalt mixture for 0.1 seconds and followed by a 0.6 second rest period. Loading is typically conducted for 5,000 cycles or until the predefined shear strain exceeds its range. At the end of the test, the permanent shear strain is determined (Brown et al., 2009).

For the SSCH test, shear stress is applied at a rate of 70 kPa per second depending on the test temperature. The stress level is maintained for 10 seconds then is reduced to 0 stress at a rate of 25 kPa per second (Brown et al., 2009). The test continues for an additional 10 seconds at a 0 stress level.

The FSCH test is performed at 10 different frequencies of 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz at a specific temperature (Chowdhury, 2002).

Figure 15: Superpave Shear Tester (FHWA, 2000)

Uniaxial Shear Tester

The Uniaxial Shear Tester was developed as part of the cooperation between the University of California Pavement Research Center and Czech Technical University in Prague. This test measures the shear resistance of asphalt mixtures. The asphalt mixture test specimens are cylindrical and measure 150 mm in diameter by 50 mm in height with a hole 50 mm in diameter that is cored through the center of specimen. To perform the test, a hollow cylindrical specimen is placed inside a steel cylinder and the load is applied through the knee joint on a steel insert placed in the centre of the specimen shown in Figure 16 (Zak et al., 2017). The steel insert is pushed down through the asphalt mixture specimen and stimulates the shear load in the tested asphalt mixture (Zak et al., 2017). The vertical deflection of the steel insert is measured as the steel insert is loaded. To understand the correlation between the UST and the RSCH test, the test procedures include applying 30,000 cycles of haversine shear pulses at 69 kPa for 0.1 seconds followed by a 0.6 second rest period at the test temperature of 50°C. (Zak et al., 2017). The study concluded that the shear value obtained from the UST test has a good correlation with the RSCH test. If there is a limitation to the loading frame, monotonic loading may also be adopted for the UST test.

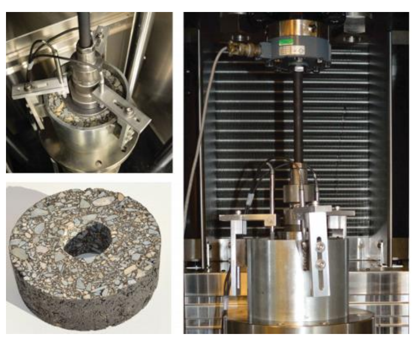

Figure 16: Uniaxial Shear Tester (top view, hollow cylindrical specimen, UST placed in UTM Chamber (Zak et al., 2017)

Monotonic Test

A monotonic loading mode is used to apply a high level of strain to the asphalt mixture to capture the asphalt mixture's resistance to high temperature permanent deformation as shown in Figure 17. In addition, a constant strain rate is applied until the peak load is reached.

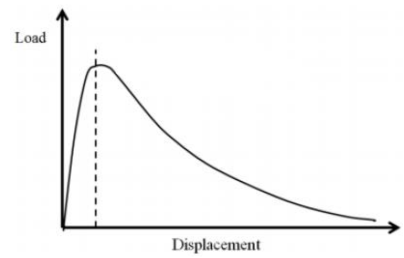

Figure 17: Typical Plot of Monotonic Test Results (Chiangmai, 2014)

Marshall Stability Test

The Marshall stability test was developed in the 1940s to measure the strength of an asphalt mixture and its peak resistance load during a constant rate of deformation. The Marshall stability test standard for sample preparation and test procedure are discussed in ASTM D6926 and ASTM D6927, respectively (Brown et al., 2009, p.312). The Marshall Stability test involves applying a compressive load at a rate of 51 mm/min to a cylindrical specimen 101.6 mm in diameter and 63.5 mm high with a temperature of 60°C using a Marshall testing frame, as shown in Figure 18, or a universal testing machine equipped with suitable load and deformation (Brown et al., 2009, p.312). This test provides the maximum load required to fail the specimen and the flow index value which is the asphalt mixture sample’s maximum vertical deformation at the maximum load (Brown et al., 2009, p.312). From these values, the Marshall stiffness index, the maximum load (Marshall Stability) over the flow index, can be determined, which represents the asphalt mixture stiffness, and hence its resistance to permanent deformation (Brown et al., 2009, p.312).

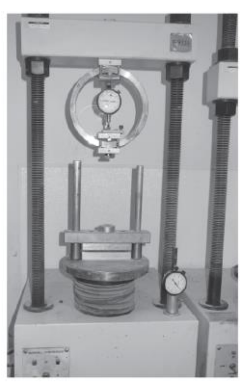

Figure 18: Marshall Proving Ring and Flow Meter (Asphalt Institute, 2014)

Hveem Stabilometer Test

The Hveem stabilometer test provides an indication of the asphalt mixture’s ability to resist deformation under load. Similar to the Marshall stability test, this test involves applying a compressive load to a cylindrical specimen 101.6 mm in diameter and 63.5 mm high with a temperature of 60°C (Brown et al., 2009, p.313). A photo of the test frame is presented in Figure 19. The Hveem stabilometer test standard for sample preparation and test procedure is discussed in ASTM D1561 and ASTM D1560, respectively (Brown et al., 2009, p.313). This test measures the lateral pressure transmitted through a specimen from the applied vertical load and presents it as an index in a scale ranging from 0 to 100. The higher the scale value, the greater the ability of the asphalt mixture to resist deformation. The Hveem Stabilometer test values are indicative of aggregate characteristics (Brown et al., 2009, p.313).

Figure 19: Hveem Stabilometer (Asphalt Institute, 2014)

IDEAL Rutting Test (RT)

The IDEAL RT test, developed by Fujie Zhou of Texas A&M University, evaluates the shear resistivity of an asphalt mixture (Cooper, 2020). The test involves applying a compressive load at the rate of 50 mm/min to a cylindrical specimen 150 mm in diameter and 62 mm high that is constrained by a rigid fixture. The test temperature could vary but it is typically performed at 50°C to match the Hamburg wheel tracking test. In this test, as shown in Figure 20, two separate shear planes are developed upon the compressive load being applied to the specimen (EvothermWMA, 2020). The test provides the maximum shear resistivity of the asphalt mixture known as the RT_{index}. The higher the index value, the greater the material's resistivity to shear deformation. The test determines the maximum vertical displacement at the peak load which is the result of both non-damage stage deformation and damage stage deformation. The study conducted by Fujie Zhou shows that the IDEAL RT test has a good correlation with both the HWTD and APA tests.

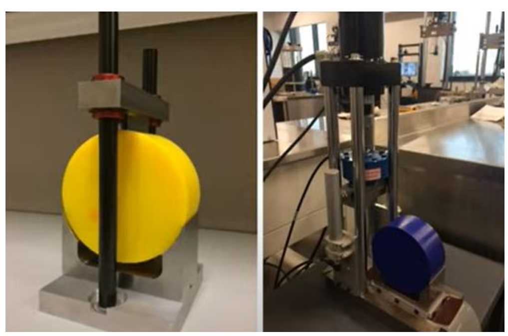

Figure 20: DEAL RT Test Fixture (EvothermWMA, 2020)

Table 5 summarizes the aforementioned performance tests used to evaluate the rutting susceptibility of asphalt mixtures in terms of equipment cost, specimen fabrication, test results and data analysis complexity, practicality for design and quality assurance, correlation to field performance, and test variability.

Table 5: An Overview of Asphalt Mixture Performance Tests for Rutting Resistance Evaluation (NCHRP 20-07/Task 406, 2018), (EvothermWMA, 2020), (Aschenbreber, 1992), (Brosseaud et al., 1993)

Laboratory tests for Rutting	**Equipment and Cost**	**Test Analysis Complexity**	**Practicality for Mix Design and QA**	**Correlation to Field Performance**	**Test Variability**
Hamburg Wheel Tracking Test (AASHTO T324)	Hamburg Wheel-Tracking device and saw for cutting specimens $ 40,000-70,000 US	Simple	Good	Good correlation to pavement sections in Colorado and Texas	Medium (COV=10-30%)
Asphalt Pavement Analyzer (AASHTO T340)	Asphalt Pavement Analyzer $ 120,000 US	Simple	Good	Good correlation to pavement sections on FHWA ALF, WesTrack, NCAT Test Track, MnRoad, and in Georgia and Nevada	Medium (COV=20%)
French Rutting Tester (LC26-410)	French Rutting Tester $ 85,000 US	Simple	Good	Good correlation to Field in Colorado	Medium (COV<=20%)
Flow Number Test (AASHTO T378)	Asphalt Mixture Performance Tester, Core drill, environmental chamber, saw for cutting specimens $ 112,000 US	Fair	Fair	Good correlation to pavement sections on FHWA ALF, WesTrack, NCAT Test Track, MnRoad	High (COV>30%)
Superpave Shear Tester (AASHTO T320)	Superpave Shear Tester, Environmental chamber, saw for cutting specimens The cost of testing device is unknown	Fair	Fair	Good correlation to pavement sections on FHWA ALF, WesTrack, and MnRoad	Unknown
Uniaxial Shear Tester	Testing Frame, Core drill, environmental chamber, saw for cutting specimens $100,000 US	Fair	Fair	Unknown	Unknown
Marshal Stability Test ASTM D6926 and ASTM D6927	Marshall Apparatus $ 10,000 US	Simple	Good	Unknown	Medium COV<=16
Hveem Stabilometer Test ASTM D1561 and ASTM D1560	Hveem Stabilometer $ 10,000 US	Simple	Good	Unknown	Medium (COV=<20%)
IDEAL Rutting Test (IDEAL RT)	Testing Frame (Same as SCB and Ideal CT), Ideal RT Jig $ 10,000 US	Simple	Good	Good	Medium (COV<15%)

Conclusions

Past studies suggest that the volumetric approach alone might not necessarily provide a comprehensive understanding of an asphalt mixture's behaviour at high in-service temperatures. This requires a level of performance testing to be included as part of the design stage to ensure an acceptable level of rutting resistance at the desired reliability level. This paper provides a detailed summary of available test methods to capture the rutting resistivity of the asphalt mixture. Since highway agencies have only been practicing asphalt mixture designs and asphalt binder specifications in their attempts to capture the rutting susceptibility of asphalt pavements, there is a lack of the appropriate performance testing required to investigate the rutting performance of asphalt mixtures. For those projects where reliability is important, it is recommended to conduct some sort of performance testing to determine the effect of both binder and aggregate on the permanent deformation at high in-service temperatures. Through literature review, the HWTT is recommended as an effective performance test to capture both the rutting and moisture susceptibility of the asphalt mixture. In addition, newly developed tests such as the IDEAL RT test and the Uniaxial shear test could be a good candidate tests for the quality control and quality assurance needed to capture the shear resistivity of the asphalt mixture.

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