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Experimental Assessment of Mineral Filler on the Volumetric Properties and Mechanical Performance of HMA Mixtures

Hanaa Khaleel Alwan Al-Bayati [a, b*], Abimbola Grace Oyeyi [c], Susan L. Tighe [d, e]

[a] *Ph.D. Research Associate, Centre for Pavement and Transportation Technology (CPATT), Department of Civil and Environmental Engineering, Faculty of Engineering, University of Waterloo, Waterloo, Ontario, Canada.*

[b] *Ph.D. Department of Civil Engineering, Faculty of Engineering, University of Tikrit, Tikrit, Saladin Province, Iraq.*

[c] *Ph.D. Candidate, Centre for Pavement and Transportation Technology (CPATT), Department of Civil and Environmental Engineering, Faculty of Engineering, University of Waterloo, Waterloo, Ontario, Canada.*

[d] *Provost and Vice-President Academic, Norman W. McLeod Professor of Sustainable Pavement Engineering, McMaster University, Hamilton, Ontario, Canada.*

[e] *Adjunct Professor, Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Ontario, Canada.*

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Abstract

This research is conducted to evaluate the influence of mineral filler on the volumetric properties, mechanical and field performance of Hot Mix Asphalt (HMA). Two mineral filler types, namely, Hydrated Lime (HL) and Dust Plant (DPt) were used. Three filler proportions were utilized greater than 1% which represents the most applicable percentage, especially for HL, used by the Ministry of Transportation Ontario (MTO). The effect of filler on various volumetric properties including Voids In Mineral Aggregates (VMA), Voids Filled With Asphalt (VFA), dust to binder ratio (Dp) is examined. Mechanical and predicted field performance of HMA to the best filler proportion that meets all the MTO limitations is also investigated. The obtained results indicated that the Optimum Asphalt Content (OAC), VMA, and VFA decrease as the filler content is increased. HMA mixtures that includes DPt filler had the higher values of VMA, VFA, and OAC compared to the hydrated lime. The addition of filler with 2.5% percentage is very successful for both filler types due to satisfying all MTO requirements for volumetric properties of HMA. Based on MTO specifications, the addition of 2.0% filler seems to be unsuccessful for both filler types due to lowering the Dp ratio. Mix design with 3.0% filler was also unsuccessful because of the lower value of OAC meaning that the mix is dry and there is insufficient asphalt binder to coat the aggregate particles. Besides, filler type has a significant effect on the mechanical properties of the HMA mixtures. As a filler in HMA mixtures, the utilization of HL as a portion of 2.5 % leads to a significant improvement in mixture resistance to water and freezing and thawing. The mixtures that included HL have a higher cracking resistance, greater stiffness, and a higher fracture stress than the mixtures that included DPt. Furthermore, predicted field performance indicated better outcomes for mixes with HL compared to DPt mixes.

Keywords: Volumetric Properties; Mineral Filler; Superpave Mix Design; Hot Mix Asphalt; Mechanical Performance of HMA.

1. Introduction

For the construction of road pavements throughout the world, one of the essential materials required is asphalt mixture [1]. It is widely known that asphalt mixture is a heterogeneous material that essentially consists of different

* Corresponding author: halwan@uwaterloo.ca

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constituents including asphalt, natural or recycled aggregate, fillers, and air voids. Additionally, various additives including fibers and polymers are generally utilized for enhancing its performance [2]. However, asphalt mixture is mainly composed of approximately 95% aggregate and 5% asphalt binder materials. In asphalt pavement, the aggregate particles represent a structural framework (skeleton) for the mixture; subsequently, it plays a significant role in influencing the engineering characteristics of the asphalt mixture. Whereas, the asphalt binder works like a sticky substance. The physical properties of both coarse and fine aggregates have a considerable influence on the asphalt pavement performance [3]. The design of asphalt mixtures can be described as a complicated process that requires very accurate proportions of aggregate and asphalt binder in order to achieve specific requirements of volumetric and mechanical properties [4].

To obtain the desired performance of asphalt mixtures, the volumetric characteristics of these mixes are required to be successful [5]. The concept of volumetric characteristics of asphalt mixes has been chronologically developed using different aspects as clarified in the following explanation. In 1915, Richardson observed the importance of volumetric proportions of the components of asphalt mixes related to asphalt performance. By the 1940s, Marshall suggested the combination of two concepts; namely, the degree of saturation of the voids of the mixtures by asphalt, that can be expressed as voids filled with asphalt and void volume. In the 1950s, the concept of voids in mineral aggregate and its importance in achieving asphalt durability was highlighted and became widespread due to McLeod's contribution [4].

Presently, the volumetric characteristics of asphalt mixtures are classified into two major categories: primary and secondary volumetric parameters [4]. The primary volumetric parameters are directly correlated to the relative volumes of the individual components of asphalt mixes including asphalt binder volume (Vb), aggregates volume (Vs), and air voids (Va). Whereas, secondary volumetric parameters generally refer to volumetric properties of mixtures such as Voids in Mineral Aggregates (VMA), Voids Filled with Asphalt (VFA), and Void Volume (Vv). Based on the primary volumetric parameters, volumetric characteristics of the asphalt mixtures, secondary volumetric parameters, are evaluated and determined. A brief description of the secondary volumetric parameters is presented in the following explanations:

- Vv is expressed as the air volume that is normally found between the particles of aggregate and surrounded by asphalt binder. It is evaluated as a percentage of the total volume of the asphalt mixture;
- VMA is generally expressed as a percentage of total volume of asphalt and is defined as the sum of the Vv and volume effective asphalt binder, non-absorbed, (VEAC);
- VFA is generally known as the degree of VMA filled by asphalt or it refers to the ratio of the volume of effective binder to the VMA and it is usually evaluated as a percentage [4, 5]. The expressions of volumetric characteristics for the constituents of a compacted asphalt mixture is provided in Figure 1.

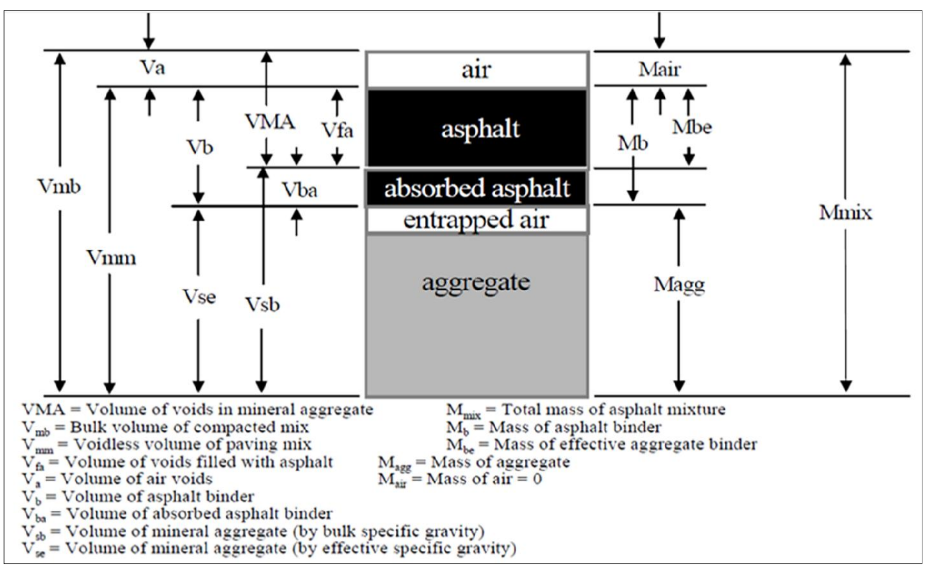

Figure 1. Constituents of asphalt mixture and expressions of volumetric properties [5]

It is widely known that the three main volumetric parameters, namely, VMA, VFA, and air voids (abbreviated VTM) represent important indicators for asphalt mixture performance. Excessive air voids, VFA, and inadequate VMA could refer to durability problems, whereas excessive VFA or insufficient air voids could result in rutting problems [4, 5]. The major factors that can impact the volumetric characteristics are the volume of aggregate, grain size, the asphalt content, the degree of compaction, and amount of fillers [4].

In the design of asphalt mixtures, there are two main methods: namely, Marshall and Superpave. These methods include the concept of volumetric properties that can be evaluated and calculated from the volumetric proportions of the components of the asphalt mixtures [5]. More precisely, the mentioned methods determine the optimum asphalt binder using volumetric characteristics of mixtures including VMA, VFA, and Vv. In addition, Superpave method has the ability to evaluate both the filler content in the asphalt mix and the percentages of initial and maximum compaction as a function of the number of gyrations in the Superpave Gyratory Compactor (SGC) [6]. In the Superpave method, the protocol of volumetric mix design was established to include limits for the three main volumetric parameters [7]. Based on the mixture's nominal maximum size (NMS) and traffic volume, Superpave method has minimum values for VMA, and minimum and maximum values of the VFA as can be shown in Table 1.

Table 1. Volumetric properties of asphalt mixtures of the Superpave method [8]

Traffic category (Note 1)	% of Theoretical maximum specific gravity			Voids in mineral aggregate (VMA) % minimum						Voids filled with asphalt (VFA)	Dust to binder ratio (Note 3)	Minimum tensile strength ratio %
				Nominal maximum aggregate size, mm								
	$N_{initial}$	N_{design}	N_{max}	3.75	25	19	12.5	9.5	4.75			
A	91.5									70-80 (Note 4)		
B	90.5									65-78		
C		96.0	98.0	11.0	12.0	13.0	14.0	15.0	16.0		0.6-1.2	80.0
D	89.0									65-75 (Note 5)		
E												

Notes:

1. Traffic category as specified in the contract documents.
2. For Traffic Categories C, D, and E Superpave 9.5 mixes shall have a VFA range of 73 to 76%, while Superpave 4.75 mixes shall have a VFA range of 75 to 78%.
3. For Superpave 4.75 mixes, the dust-to-binder ratio shall be 0.9 to 2.0. Superpave mixes with gradation that pass beneath the PCS control point in Table 4, the dust-to-binder ratio shall be 0.8-1.6.
4. For Traffic Category A, Superpave 25.0 mixes shall have a VFA range of 67 to 80%
5. Superpave 37.5 mixes shall have a VFA range of 64 to 75%.

This paper begins by reviewing existing literature on filler types and effects on the performance of asphalt mixtures, then discusses the different materials and testing methods employed in this study to investigate two types of filler with different percentage and their influence on the volumetric properties and asphalt mix performance. The study proceeds to present and discuss findings from the experimental work. It moves on to investigate and predict field performance when incorporating the optimal filler options from the experimental work and finally provides conclusions of the study.

2. Literature Review

Generally, aggregates in asphalt mixtures are classified into two main groups; namely, coarse and fine aggregates. While aggregates that are larger than 4.75 mm are categorized as coarse, aggregates that are smaller than 4.75 mm typically are categorized as fine. The existence of both aggregate types in asphalt mixtures seems to be mainly responsible for providing a skeleton to resist the repeated traffic load applications and contributing to the viscous-elastic properties of the mixture [9, 10]. With respect to aggregate size, filler refers to aggregate particles that are finer than 75 μm in size or can pass through the No. 200 sieve (0.075 mm) [10, 11].

It is generally agreed that a portion of aggregate that is suspended and freely discrete from aggregate particles in an asphalt binder can be known as a mineral filler [4, 12]. Based on this, it is reasonably postulated that mineral filler cannot be considered as aggregate or as a single component in a mixture; therefore, it is equitably counted as an integral component of mastic which is generally described as an actual binder for a mixture [4, 12]. Additionally, due to its very small size, a filler is viewed as a fine material that has an ability to modify and enhance the properties of the asphalt-concrete mixture; and therefore, the filler appears to be a modifier and is not considered as a part of aggregate gradation [10].

The role of the filler in the asphalt mixture can be described by various mechanisms. The first important role is that filler can provide more additional points of contact between the larger aggregate particles; therefore, it can be regarded as a continuation of the fraction of asphalt aggregate mixture. The stability of the mixture is increased through increasing the viscosity of the asphalt binder and altering its characteristics is another significant role for the presence of filler in the asphalt mixture [6]. Possible interaction with asphalt could be the most important function that filler particles play in the asphalt mixture. Due to its high fineness, asphalt-filler mastic is formed. In certain mastic characteristics, interactions between filler and asphalt could possibly occur that may influence the mixture's performance. However, due to its large surface area, absorption of some asphalt amounts on the filler surface is quite possible, resulting in a different performance behaviour of the asphalt mixture [13, 14].

Due to the diverse influence of filler addition on asphalt mixtures, numerous studies have investigated various aspects related to this influence and these aspects can be fundamentally classified into two main categories. The first category mainly includes the influence of filler addition on the asphalt mixture's performance. It was found that the addition of higher filler concentrations leads to strong mixtures. This was mainly attributed to better asphalt cohesivity and good stability that was obtained from a good packing distribution of the filler [10]. The addition of lime as a filler can improve the resistance of hot mix asphalt mixtures to moisture damage, reduce oxidative aging, improve the mechanical properties and resistance to fatigue and rutting, and enhance the asphalt-aggregate bond [6, 15, 16]. Including cement and nano-silica fillers in asphalt mixtures can likewise significantly improve strength to resist moisture damage [17]. Fillers can also increase the resilient modulus of an asphalt mixture [17, 18]. It was observed that the addition of fillers leads to improvement in the temperature susceptibility and durability of the asphalt binder and asphalt-concrete mixture [19-21]. It has been previously proven that mineral filler can be responsible for improving mechanical, rheological, and thermal behaviour of asphalt mixtures. Workability can be also enhanced by the utilization of mineral filler as a filling material that occupies the spaces between different aggregate sizes [6]. Moreover, mineral filler leads to improving stiffness at the upper range temperatures of asphalt mixtures and reducing stiffness at lower temperatures [4, 12]. The second category is extensively focused on the influence of filler on the asphalt binder or mastic properties. It has been previously concluded that the presence of filler is highly related to a reduced optimum asphalt content [22-24]. Mineral filler in hot mix asphalt plays a significant role in stiffening and toughening an asphalt binder. It seems to be responsible for improving adhesion of bitumen to aggregate [16]. The filler addition not acting on just improvement of HMA performance but also enhances the aggregate properties. Sebaaly et al. reported that the characteristics of the marginal aggregate that have plastic fines could improve by adding hydrated lime. This improvement is coming through the mechanisms of cation exchange, flocculation/ agglomeration, and pozzolanic reactions. As a result of these reactions, fines' characteristics would be changed; thus, they are no longer plastic, but these small particles soon agglomerate together, held together by a pozzolanic cement. Subsequently, this process improves the resistance of aggregate fines to moisture through decreasing their capability to entice and hold water [25]. In the perspective of volumetric properties, Santos-Bardini et al. [6] explored the influence of filler type and content on HMA volumetric parameters. The findings of the research revealed that VMA and VFA decrease as the filler content increases. It was concluded that lower values of VMA and VFA generally refer to the existence of thin asphalt film. It was also found that aggregate type influenced the volumetric properties.

While comprehensively scanning the literature related to the filler addition into the asphalt mixtures, it should be noted that investigation of its impact on the volumetric properties of the asphalt mixtures is rarely found in the relevant literature. As many investigations were primarily limited in assessing the performance of asphalt mixtures that included mineral filler proportions, only one characteristic; namely, optimum asphalt content that can be counted as a volumetric property was evaluated [24, 26]. Additionally, as a part of the Marshall mix design, the relationship between asphalt binder content and some volumetric properties such as VMA and VFA were examined [26-28]. To the best of the authors' knowledge, none of the literature studies mentioned above have ever explored the effect of filler on the volumetric properties according to the Superpave mix design. Additionally, in all cases, most of the studies regarding the effect of filler, especially HL on HMA performance, focus on hydrated lime contents of 1-1.5%, and these effects are generally more pronounced for higher hydrated lime contents [29]. Therefore, this paper is a comprehensive study that mainly aims to examine the influence of filler types with various proportions on various volumetric properties based on the Superpave mix design and field performance.

3. Research Objective

The main objectives of this research were to investigate the influence of different filler types of various proportions on the volumetric properties of HMA and to examine mechanical and field performance of mixtures that include the best filler proportion that meets the Ministry of Transportation Ontario (MTO) limitations. More precisely, the influence of hydrated lime (HL) with a proportion higher than 1.0% on the mechanical performance and volumetric properties of asphalt mixtures is examined. The above-mentioned percentage represents the common percentage used by the MTO.

Typically, Superpave specification standard requires asphalt mixtures to be designed with 19 mm nominal maximum aggregate size (NMAS) and a PG 64-28 binder. To achieve this goal, two different types of mineral fillers frequently employed in asphalt mixtures were used; namely, HL and dust plant (DPt) of various proportions (2, 2.5 and 3%). These were chosen to examine the influence of mineral fillers on various volumetric characteristics including VMA, VFA, dust to binder ratio (Dp), and others. Then, the mechanical performance of HMA mixtures at their respective optimum asphalt content was evaluated by various tests including: indirect tensile strength, moisture sensitivity, permanent deformation, dynamic modulus, and thermal stress restrained specimen test (TSRST).

4. Materials and Testing Procedures

4.1. Materials

Natural aggregate (NA), and HL and DPt that are used as fillers in HMA were obtained from Miller Group company. The obtained sieve analysis of NA, targeted mix design, and MTO specifications are given in Figure 2 and Table 2. After utilizing different tests and protocols, the obtained findings of the physical and mechanical properties of NA is presented in Table 3. The optical images of NA, HL, and DPt are shown in Figure 3-a, b, and c, respectively.

Table 2. Gradations, targeted mix design, and MTO specifications

Sieve size (mm)	Passing (%)	Target of mix design	MTO limitation
25	100	100	100
19	95.2	96.8	100 - 90
16	89.0	90.6	90 - 23
12.5	81.8	83	
9.5	73.2	73.3	
6.7	63.3	63.3	
4.75	57.1	55.9	
2.36	42.8	43.5	49 - 23
1.18	30.7	32.5	
0.6	22.9	25.1	
0.3	10.2	11.8	
0.15	5.4	5.5	
0.075	2.1	3.8	8 - 2

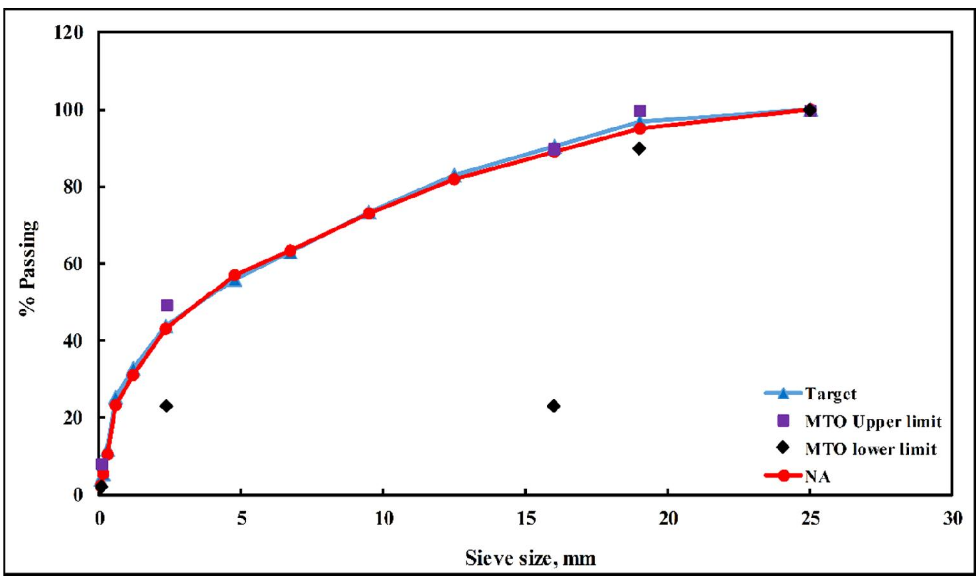

Figure 2. Particle size gradations of natural aggregate (NA)

Table 3. Physical and mechanical properties of NA

Aggregate properties	NA
Bulk Relative Density (BRD), (ASTM C 127)	2.658
Bulk Relative Density (SSD), (ASTM C 127)	2.679
Absorption, %, (ASTM C 127)	0.8
Micro-Deval Abrasion Loss, %, (ASTM D6928)	15.89
Fractured Particles, %, (ASTM D5821)	95.5
Aggregate Crushing Value (BS 812-110)	19.48
Freezing & Thawing (LS- 614)	17.4

3-a NA **3-b HL** **3-c DPt**

Figure 3. Optical images of NA, HL, and DPt.

4.2. Testing Procedures

All experimental tests were conducted in the Centre for Pavement and Transportation Technology (CPATT) in the University of Waterloo. However, different tests were performed in this study. The research methodology is outlined in Figure 4.

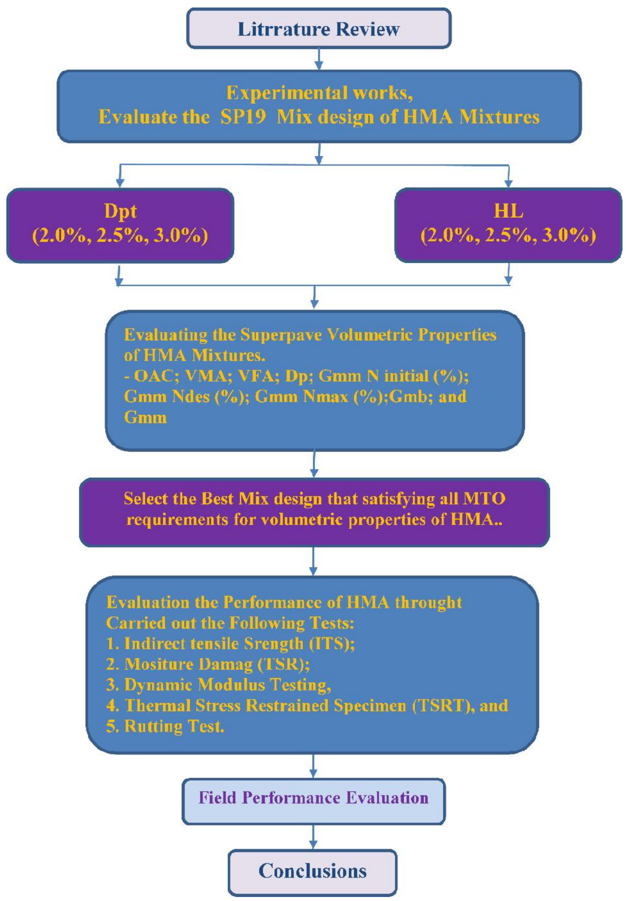

Figure 4. Research methodology

4.3. HMA Superpave Mix Design

HMA Superpave mix design was in accordance to AASHTO R 30-2 (2006). The equivalent single-axle load ranged between 10 and 30 million. The design gyration level (Ndes) was 100, and the maximum gyration level (Nmax) was 160. Mixing and compaction temperatures were defined by setting viscosity to 1.7 and 2.8 Poises respectively. The gradation of aggregates for each sample were prepared individually. In order to simulate short term aging and ensure absorption of asphalt binder by aggregates, samples were kept at the compaction temperature of 150 °C for two hours after binder addition and mixing. Mixing was performed using a drum mixer at 163 °C temperature. To evaluate the mechanical performance of the HMA mixtures, the loose HMA mixtures were subjected to short-term conditioning in a forced-draft oven for four hours at 135 °C prior to compaction to simulate plant mixing and placement effects according to AASHTO R 30-02, 2006. The Superpave gyratory compactor as shown in Figure 5 was used for compacting the samples which appeared as shown in Figure 6.

Figure 5. Superpave gyratory compactor

Figure 6. Samples after compaction

4.4. Mix Design Blend with Filler

Superpave mix design was performed according to AASHTO R 30-2 (2006). For filler addition, three proportions (2, 2.5 and 3%) were used to determine the mix blend. The mixture that included two filler types with various proportions is given in Table 4.

Table 4. Mix design blend with different filler proportions

Filler content, %	Aggregate type, %			
	CA[a] #1, HL8 stone	CA#2, ¼ chip	FA[b] #1, Manufactured sand	FA#2, Blend sand
2.0	40	12	36	10
2.5	40	12	35.5	10
3.0	40	12	35.0	10

Note: CA[a] = Coarse aggregate; FA[b] = Fine aggregate

4.5. Mixture Performance Testing

4.5.1. Indirect Tensile Strength (ITS) and Moisture Sensitivity (TSR) Test

In accordance with AASHTO T-283 method, the ITS was determined for mixtures that included both types of fillers: DPt and HL, to assess the resistance of mixtures to cracking. The specimens with air voids of 7% ± 0.5 were compacted using a Superpave gyratory compactor with a height of 95 ± 5 mm. The samples were divided into two sets of three specimens: unconditioned strengths (control) and conditioned strengths. For the unconditioned specimens, the test temperature and loading rate were 25 °C and 50 mm/min, respectively, whereas the second set was utilized for moisture-conditioning. This conditioning begins with achieving a saturation of the specimens between 70% and 80%. Then, the specimens were placed in a freezer for a minimum of 16 hrs at a temperature of -18±3 °C and were then placed in a hot water bath at a temperature of 60 ±1 °C for 24 ±1 hrs. To prepare the samples for testing, the specimens were removed from the hot water bath and kept in a water bath at a temperature of 25 ±0.5 °C for 2 hrs ±10 mins.

The tensile strength ratio (TSR) was determined by conditioned strength divided by unconditioned strength. According to the specification of [8], the TSR should be more than 80%. The ITS and TSR values are calculated using the following equations:

$$ITS = \frac{2000P}{\pi t D} \quad (1)$$

Where: ITS is the indirect tensile strength, kPa; P represents the maximum load, N; t is the thickness of sample before test, mm; D represents the sample diameter, mm; and π is equal to 3.14.

$$TSR = \frac{ITS_{con.}}{ITS_{uncon.}} \quad (2)$$

Where: TSR is the tensile strength ratio; ITScon. represents the tensile strength of a conditioned sample; ITSuncon. represents the tensile strength of an unconditioned sample.

4.5.2. Hamburg Wheel Rut Test

In this study, the Hamburg Wheel Rut Tester (HWRT) was used to examine the rutting resistance of the asphalt mixtures using the AASHTO T 324-04 standard. Each mix of air voids of 7 ± 2% were compacted using a Superpave gyratory compactor with a height of 63 ± 2 mm. The specimens were tested under the impact of a solid steel wheel, a load equivalent to 705 ± 4.5 N, in a hot water bath at 50 °C for 10,000 cycles that are equivalent to 20,000 passes, or until a rut depth of 20 mm was reached [30]. To determine the rutting depth, Linear Variable Differential Transducers (LVDTs) were utilized to realize the impression depth under the wheel loads. For each mix, the test was replicated four times to obtain reliable results.

4.5.3. Shear flow of HMA mixture

To obtain a better understanding of the influence of the filler type on the rutting resistance for the HMA mixtures, the shear upheave on the rutting sides was evaluated. To examine the shear upheave, the following method was used. By using simple techniques such as rutting bar, the total rutting depth was firstly determined and named $total_{rutting\ depth}$. The application of this procedure simulates the method used to evaluate rutting depth in the field. As previously discussed, the rutting depth was measured in the lab using the HWRT test. The obtained value was named $lab_{rutting\ depth}$. The shear flow, known also as lateral creep, was calculated by taking the difference between $total_{rutting\ depth}$ and $lab_{rutting\ depth}$ as in the following equation. A schematic drawing of the method used to evaluate shear flow is provided in Figure 7.

$$Shearflow\ (upheave) = total_{rutting\ depth} - lab_{rutting\ depth} \tag{3}$$

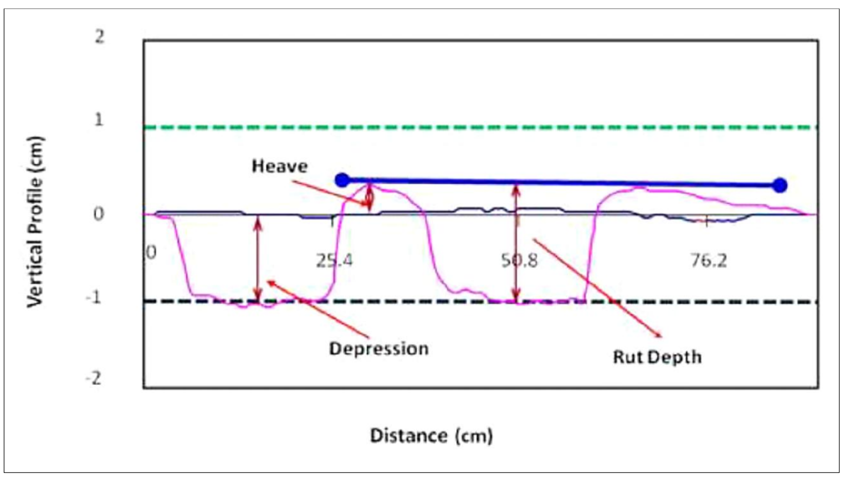

Figure 7. Surface profile for calculating shear upheave [31]

4.5.4. Thermal Stress Restrained Specimen Test (TSRST)

The CPATT asphalt shearbox compactor (PReSBOX) was used to compact beam specimens that were dimensioned approximately 390 mm x150 mm x130 mm in length, height, and width, respectively. Then, the beams were saw-cut into TSRST specimens at dimensions of 250 mm × 50 mm × 50 mm with air voids of 7±1% that represent the typical values for compacted beams [32, 33]. To simulate the plant mixing and placement effects, the loose HMA mixtures were exposed to a short-term condition at 135 °C for a period of four hrs before the compaction based on AASHTO R 30-02 (2006). The test specimens were conditioned at 5 °C in an environmental test chamber for six hrs. While an initial tensile load was applied to the compacted beams, simultaneously, the specimens were exposed to a constant cooling rate of -10 ºC/hr and were restrained from contraction by re-establishing the initial length of the specimen.

4.5.5. Dynamic Modulus Test

Following the AASHTO TP 62-07 specification, this test was performed to determine stiffness for HMA mixtures at different temperatures (-10, 4, 21.1, 37, and 54.4 °C) and frequencies (25, 10, 5, 1, 0.5, 0.1Hz). The Superpave gyratory compactor was utilized in compacting the cylindrical specimens, which were then cored and cut into 150 mm height and 100 mm diameter dimensions with air void content of 7 ± 1%. A master curve was used to evaluate the dynamic stiffness (MPa) versus the reduced frequency (Hz).

5. Results and Discussion

5.1. Volumetric Properties of the Mixture with Filler Addition

The laboratory data on the volumetric characteristics of HMA mixtures that included different filler types at various proportions are tabulated in Table 5. More details on the results of the volumetric properties are discussed in the following sections.

Table 5. Volumetric characteristics of mixtures with different filler types at various percentages.

Filler type / Property	Dust plant, %			Hydrated lime, %		
	2.0	2.5	3.0	2.0	2.5	3.0
OAC (%)	4.9	4.83	4.54	4.81	4.79	4.26
VMA (%)	14.65	14.5	13.4	14.5	14.2	13.2
VFA (%)	72.69	72.50	70.10	72.30	72.00	69.50
Dp	0.43	0.6	0.8	0.47	0.6	0.8
Gmm N initial (%)	88.56	88.60	88.30	88.01	88.02	88.03
Gmm Ndes (%)	96.0	96.0	96.0	96.0	96.01	96.0
Gmm Nmax (%)	97.3	97.10	97.19	97.21	97.22	97.00
G_{mb}	2.398	2.40	2.425	2.401	2.407	2.423
G_{mm}	2.498	2.50	2.526	2.501	2.507	2.524

5.1.1. Optimum Asphalt Content (OAC)

The OAC in HMA mixtures with two different filler types is graphically analyzed in Figure 8. A comparable performance that can be represented as an exponential equation for both filler types is registered. It is observed that the optimum asphalt binder content decreases when the filler percentage is increased. This behaviour can be mainly attributed to the fact that an increase in the filler amounts can lead to filling the voids that generally exist between aggregate particles, resulting in a reduction of the voids in the mineral aggregate. Thus, the available space for asphalt binder is decreased [34]. Huang stated that the required asphalt binder content decreases to form the same quantity of mastic for lubricating the aggregate when filler content is increased. Depending on the workability of the asphalt mixtures, a higher filler content lowers the required asphalt binder due to the compaction of the mixtures on the needed air voids [11]. It is noteworthy that a significant decrease in the optimum asphalt binder content is observed when filler content is increased from 2.5% to 3% for both filler types, which is correspondence with Huang's conclusion [11]. Besides, it has been previously concluded that the presence of filler is highly related to reduce optimum asphalt content [18, 22-24]. Additionally, the results demonstrated that the mixtures that included HL at different percentages have a lower OAC than the mixtures that included a DPt filler type. It has been previously reported that hydrated lime works as an inert filler and it physically reduces the optimum asphalt content by filling voids [35]. Besides, this reduction in OAC of HMA with HL could be because of the higher specific surface of this filler, which can result in a large surface activity [6].

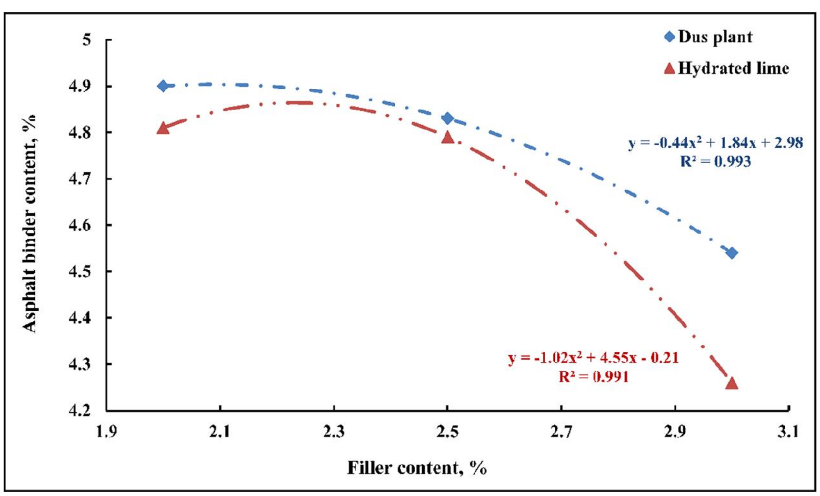

Figure 8. Optimum asphalt content for mixtures with different filler types

5.1.2. Voids in Mineral Aggregates (VMA)

Figure 9 illustrates the effect of filler types with different percentages on VMA of HMA mix design. It was demonstrated that an increase in filler content can lead to a decrease in VMA of the mixture for both filler types. The lowered VMA value could possibly indicate the existence of a thin asphalt film around the aggregate particles. It has been previously found that the utilization of high amounts of filler produces a thin asphalt film which could be more likely to be a detrimental factor with regards to mixture durability [6]. These results correspond closely to the outcomes of OAC, which the optimum asphalt binder content decreases when the filler percentage is increased. As the authors reported in the literature review that VMA and VFA decrease as the filler content increases, and lower values of these properties generally refers to thin asphalt film [6]. Also, this result is in conformity with the results of a previous study [6]. The findings also indicate a slight variation between two different filler types on VMA. However, compared to the required percentage of the minimum VMA to MTO specification that is typically accounted as 13 for this category of the HMA mix design, the obtained outcomes were higher than the required percentage, resulting in a highly successful filler addition for both different types.

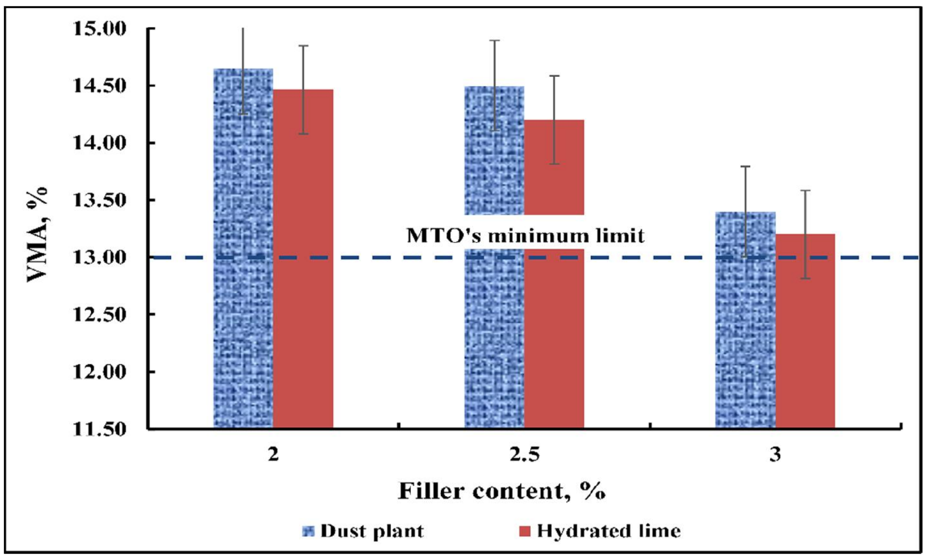

Figure 9. Voids in mineral aggregates (VMA) for mixtures with different filler types

5.1.3. Voids Filled with Asphalt (VFA)

The influence of various filler types with different proportions on VFA for HMA is presented in Figure 10. VFA defined as the ratio of the volume of effective binder to the VMA; it is synonymous with the asphalt-void ratio [36]. VFA is one of the crucial properties of HMA because it represents a measure of relative durability, and there is a strong relationship between this property and density [37]. When the value of VFA is extremely low, the quantity of asphalt required to provide durability and density under the effect of traffic and bleed is not sufficient. Therefore, the VFA represents an essential design criterion. The findings showed that a similar behaviour for both filler types is obtained. It is noted that the VFA value proportionally decreases depending on an increase in the filler content. As explained in VMA property, the existence of a thin film appears to be the main reason behind the reduction in the VFA values. For the influence of different filler types on VFA, an insignificant variance between various fillers on this volumetric property is observed. The comparison of VFA values required for the MTO specification range between 65% and 75%, and it is found that the research findings were higher than the lower limit percentage, corresponding to no impact of a filler type with various proportions on this volumetric property.

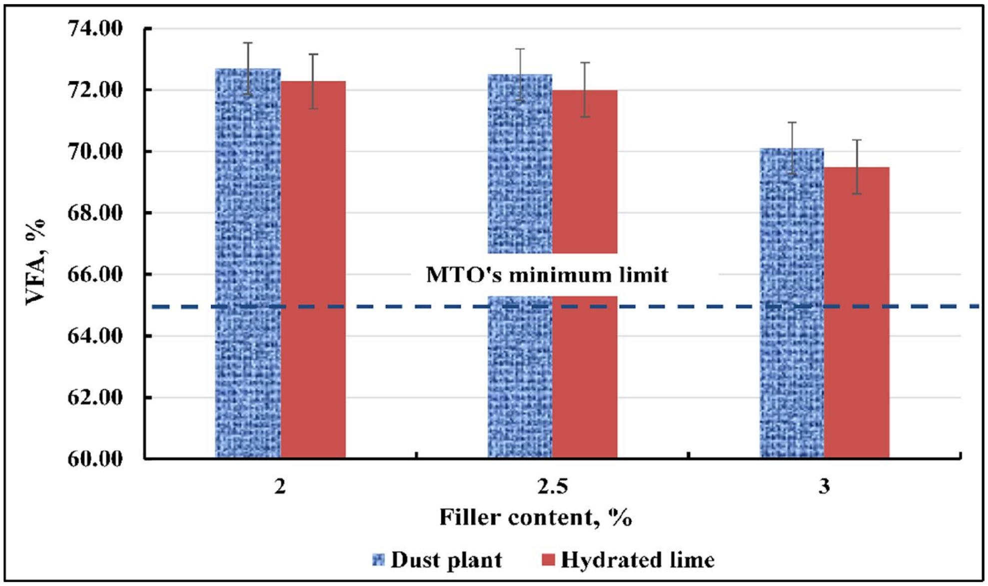

Figure 10. Voids filled with asphalt (VFA) for mixtures with different filler types

5.1.4. Dust to Binder Ratio (Dp)

Figure 11 demonstrates the Dp ratio (also known as the dust proportion) which represents another mixture design criterion. Dp is defined as the ratio of aggregates expressed as a percent by weight that can pass through the 0.075 mm sieve (#200) to the effective asphalt content or optimum asphalt binder accounted as a percentage by weight [36]. The findings of the investigation indicated that the Dp ratio seems to be directly proportional to filler content for both different filler types. The Dp proportion increases when the filler content is increased; therefore, it can be concluded that the Dp proportion behaves inversely compared to other volumetric properties for both filler types. The outcomes also revealed that the Dp values at 2% filler content are 0.43 and 0.47 for dust and lime filler types, respectively. It is interesting to note that the experimental values of Dp with filler content 2% were 0.6 for the dust and lime filler types, whereas the obtained values of Dp with filler content 3% were 0.8 for both different filler types. Depending on the MTO specification that requires an acceptable range for Dp between 0.6 and 1.2, it can be concluded that the obtained values of Dp for the mix design with a filler content of 2% are lower than the minimum required values, resulting in the mix design that is unacceptable for both filler types whereas the experimental values of Dp for mix design with filler content 2.5% and 3% were within the acceptable range of MTO specifications for both filler types. It has been previously reported that low Dp values generally indicate unstable mixtures, whereas high Dp values could possibly refer to a lack of sufficient durability [36].

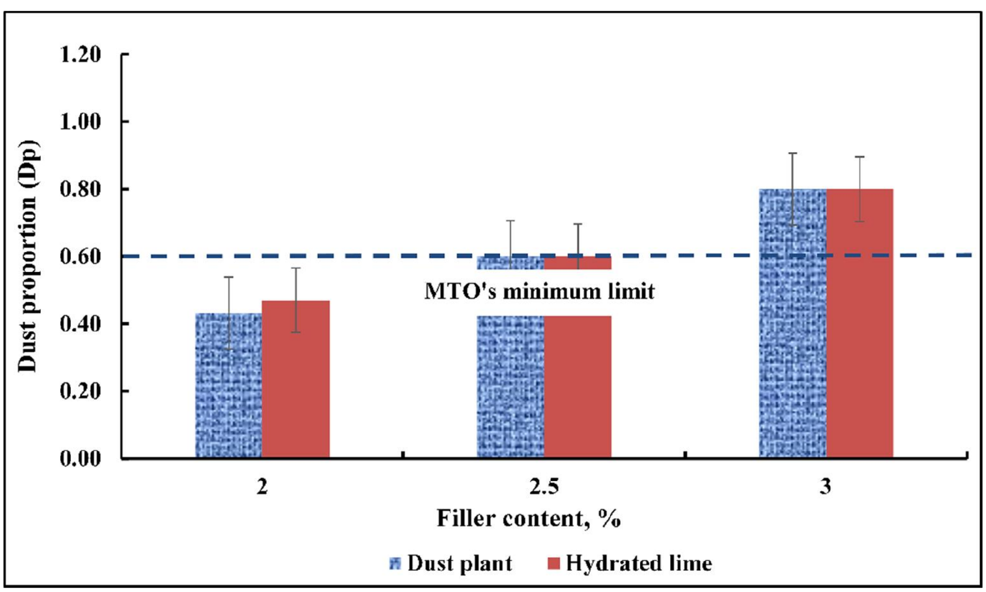

Figure 11. Dust proportion (Dp) for mixtures with different filler types

5.1.5. Maximum Theoretical Specific Gravity (Gmm) & Bulk Specific Gravity (Gmb)

Generally, Gmm denotes the ratio of the mass of the asphalt and aggregate mixture to the volume that does not include the air voids, whereas Gmb indicates the ratio of the mass of the asphalt and aggregate mixture to the volume that includes the air voids [36]. The behaviour of the properties Gmm and Gmb for HMA using different filler types is displayed in Figure 12. It was observed that there is a comparable behaviour to Gmm and Gmb for different filler types with various percentages. When the filler content is increased, there is an increase in the Gmm and Gmb values for both filler types, indicating that there is no influence of filler type on these properties.

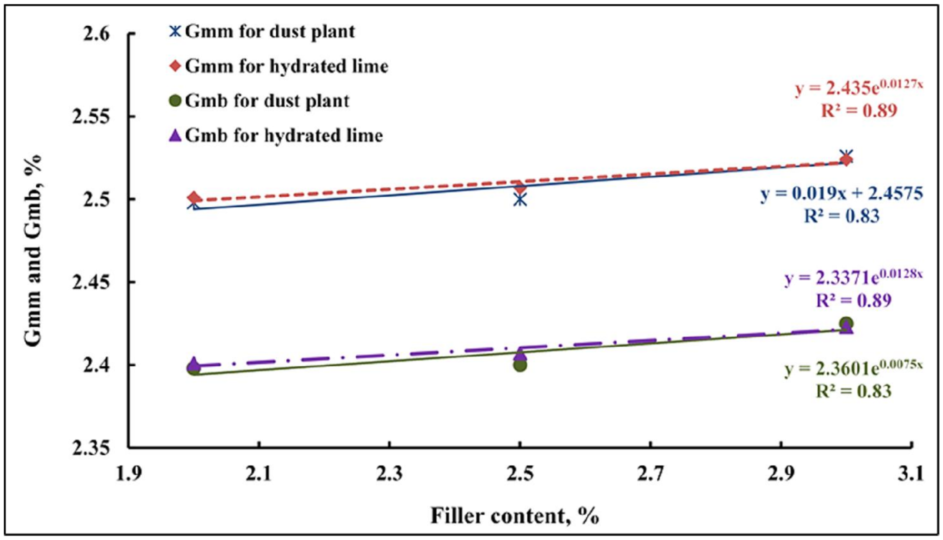

Figure 12. Gmm and Gmb of mix at different filler percentages and types

5.1.6. Evaluation of Mixture Design with Filler Addition

An additional important characteristic of mixture volumetric requirements is the mixture density during compaction at Nini and Nmax. The detailed features of this required property that was obtained for mixtures with different filler types and various percentages are tabulated in Table 6. The previous laboratory results of different filler types with various proportions and the obtained data in Table 6 emphasized that the addition of filler with 2.5% is highly successful for both filler types due to achieving all MTO requirements for volumetric properties of HMA. It is concluded that the addition of filler with 2.0% is unsuccessful for both filler types because of a dust to asphalt binder ratio that was lower than the MTO specification. The addition of filler with 3% is also unsuccessful for both filler types. Mixture with 3.0% filler had a lower value of OAC, meaning that the HMA mixture is dry and the asphalt binder is not sufficient to completely coat the aggregate particles. Therefore, the mechanical properties of asphalt mixtures are evaluated with a filler percentage of 2.5% for both filler types; namely, DPt and HL.

Table 6. Results of the property of mixture density during compaction

Volumetric design	Dust plant, %			Hydrated lime, %		
	2.0	2.5	3.0	2.0	2.5	3.0
G_{mm} $N_{initial}$ (%)	88.56	88.60	88.3	88.01	88.02	88.04
G_{mm} $N_{des.}$ (%)	96.00	96.00	96.00	96.00	96.01	96.01
G_{mm} N_{max} (%)	97.3	97.1	97.2	97.21	97.22	97.01

5.2. Evaluation of Asphalt Mixture Performance

5.2.1. Effect of Filler on ITS & TSR of Mixtures

In general, the type of filler has a considerable effect on ITS & TSR of mixtures as shown in Figure 13. There is an obvious difference in the strength of mixtures in terms of conditioned and unconditioned. In terms of the dry case (unconditioned), the ITS value of the mixture that included DPt filler is higher than the mixture using HL filler type. The reason behind this could possibly be due to a high OAC content that leads to a strong adhesion between asphalt binder and aggregate. The opposite behaviour is registered for the conditioned (wet) mixtures. As a filler material, the utilization of HL resulted in a considerable improvement in the mixture resistance to water and freezing and thawing (conditioning of samples includes freezing at a temperature of −18±3 °C for 16 hrs for saturated samples, then thawing at 60 ±1 °C for 24 ±1 hrs). The addition of HL can enhance strength bond between aggregate and asphalt binder, and could react with highly polar molecules of asphalt binder [12]. It has been previously reported that HL considerably decreases moisture susceptibility, greatly improves asphalt binder-aggregate bond, and enhances the resistance of mixtures to water-induced damage [15]. According to Gorkem & Sengoz's study, the HL addition enhances the adhesion between aggregate and binder by its interaction with carboxylic acids in the asphalt and formation of insoluble salts that are easily adsorbed at the aggregate surface [20]. Whereas, the opposite behaviour is recorded in terms of ITS for the mixtures that included DPt; the outcome indicates that the conditioned ITS has a lower value than the unconditional ITS. The reason on behind this could be, as Hamed et al. reported, due to losing the adhesion of between aggregate-binder or the binder adhesion, which is resulting from exposure to moisture through the samples' conditioning process [17]. On the other hand, the ITS can be utilized for evaluation of the cracking properties of asphalt mixtures. It was found that increasing the values of tensile strength for asphalt mixtures corresponds to a higher resistance to cracking [20]. Based on this, the higher value of conditioned ITS of the mixture that included HL is capable of withstanding higher tensile strains prior to cracking compared to the mixture that included DPt filler. The TSR was measured to investigate the influence of filler type on the characteristics of moisture susceptibility of asphalt mixtures. As shown in Figure 13, TSR values for mixtures of both filler types have a higher value than the MTO requirements. This indicates that mixtures with both filler types have a good resistance to moisture damage. It is interesting to note that a significant difference is recorded in the TSR value of HL and dust plant with approximated values of 135% and 90% respectively. This indicates that the addition of HL has a more pronounced influence on the moisture susceptibility characteristics than DPt filler. It is well known that Hydrated lime can control water sensitivity and works as an antistrip to prevents moisture damage [25].

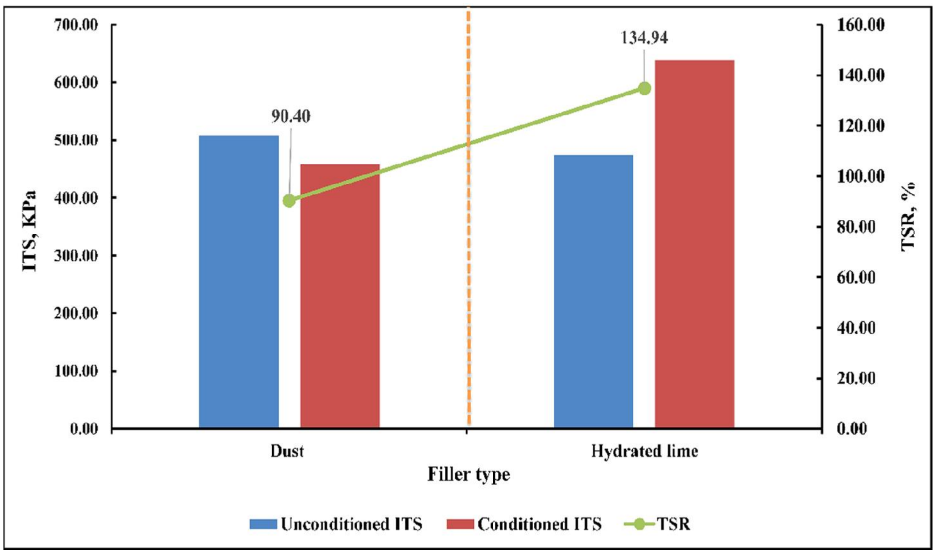

Figure 13. ITS and TSR values of mixtures with different filler types

5.2.2. Effect of Filler on the Permanent Deformation and Rutting Depth

Figure 14 demonstrates the average rutting depth curves of four samples of HMA mixtures for each filler type versus the number of wheel passes. Generally, the outcomes reflect the combined impact of both rutting and moisture damage. As it is well known, moisture damage is taken place after the stripping inflection point (SIP) occurs. The SIP is defined as the intersection between creep slope and stripping slope, or it is the number of passes when stripping starts. The obtained results indicate an outstanding performance of mixtures that included both filler types, exhibiting high resistance to moisture damage and permanent deformation. However, the filler type highly affects the rutting resistance. Based on the obtained outcomes, the HL has a considerable effect on the permanent deformation (rutting). The utilization of HL in HMA mixtures leads to increasing stiffness, which is higher than DPt filler. As previously reported, HL results in an increase in the HMA mixture's stiffness, bitumen softening point, and bitumen mastic [12, 25]. Besides, this finding is confirmed by many studies' conclusions that have illustrated; hydrated lime in asphalt mixtures can reduce the permanent deformation (rutting) of the pavement because of its distinct stiffening effects, moisture-associated damage by enhancing the aggregate–asphalt bonding, and long-term oxidative aging possibility [38, 39]. In addition to its capability to resist micro-crack development within the mix [39]. Tarrer also found that hydrated lime reacted with silica and alumina aggregates in a pozzolanic manner that added considerable strength to the mixture [25].

To compare different levels of rutting depth of mixtures with various filler types, the experimental results are drawn up as shown in Figure 15. Interestingly, the HL shows the similar trends of rutting resistance that were measured by utilizing HWRT, total rutting depth (manually) and shear upheave. Thus, the mixtures that include HL as a filler have a greater rutting resistance or a lower permanent deformation than those that include DPt filler. This consequence is widely acceptable in the relevant literature due to the behavior of HL within the HMA mixtures, as mentioned above.

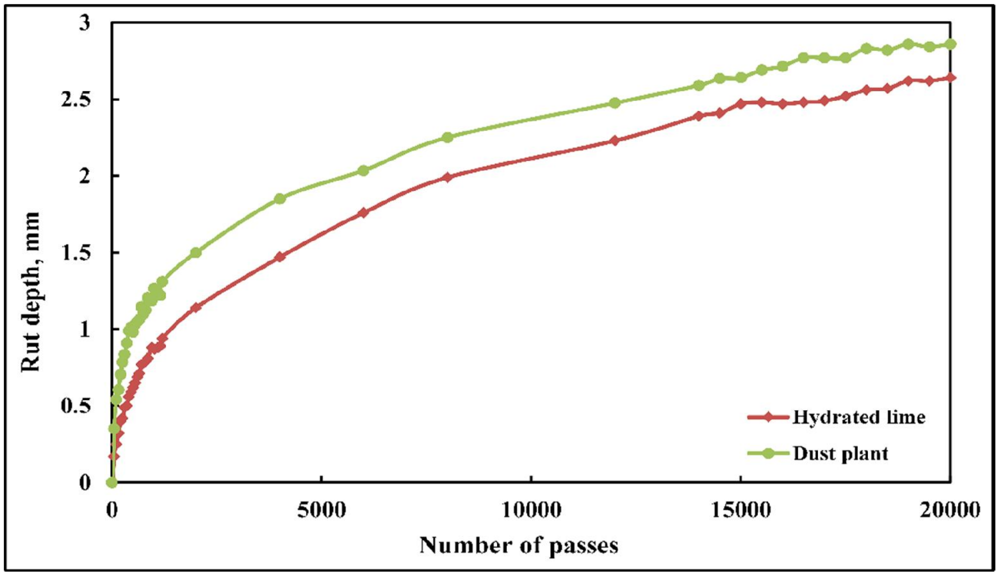

Figure 14. Influence of filler type on the permanent deformation of the mixture

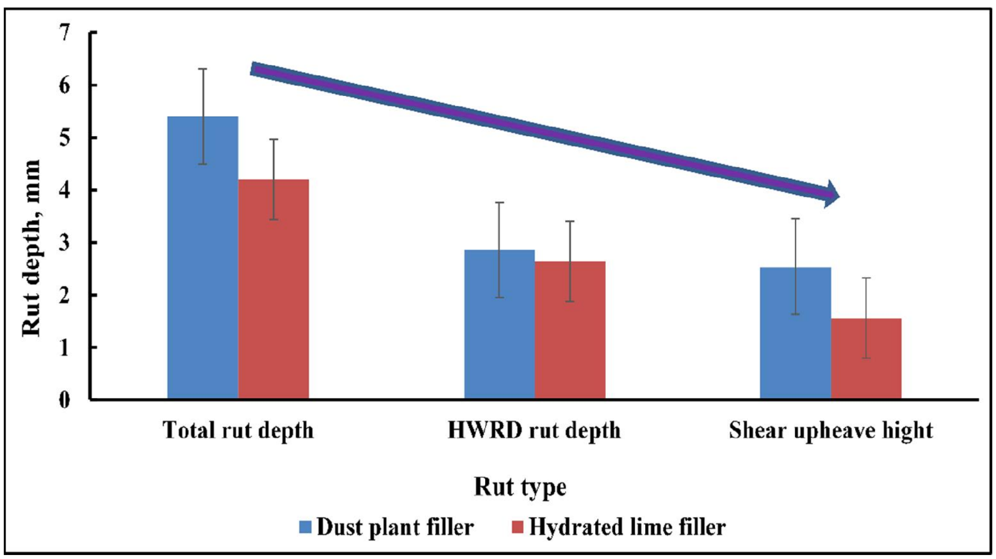

Figure 15. Rutting depth for mixtures with different filler types

5.2.3. Effect of Filler on the Thermal Crack Resistance

The TSRST results reveal a considerable reduction (i.e. more negative) in the fracture temperature, indicating a greater resistance of the mixture to low-temperature thermal cracks. In Table 7, the tabulated outcomes illustrate that the filler type has an impact on the fracture thermal stress and the failure temperature. The average values of the fracture temperature are plotted in Figure 16. It is noted that the average fracture temperature is reduced due to the HL addition. This can be explained by the fact that the use of HL in the mixtures leads to higher mixture stiffness than DPt as mentioned previously. These results correspond closely to the outcomes of rutting, high stiffness, and less low-temperature crack resistance. Besides, Lesueur et al. stated that "in line with the observation that hydrated lime does not exhibit a higher stiffening effect than mineral filler at low temperature, no negative effect on the thermal cracking resistance is reported in the literature" [29]. The maximum reduction of the fracture temperature was up to -0.4°C less than the corresponding low-temperature performance grade of the respective asphalt binder used. This is due to the HL addition, whereas the utilization of DPt in HMA leads to a considerable decrease in the average fracture temperature.

The average fracture temperature is -30.23 °C and meets the corresponding low-temperature performance grade, -28.0 °C, of the respective asphalt binder used. Hence, this filler type, DPt, appears to be highly successful in low-temperature regions such as Canada. The mean of the fracture stress of asphalt mixtures with various filler types is presented in Figure 16 and Table 7. It is known that a high value of the fracture stress corresponds to a large resistance to thermal cracks and vice versa. Surprisingly, the obtained results indicate that the fracture stress levels of the mixtures that included HL are higher than the fracture stress of mixtures that included DPt filler. This outcome is completely different from the average fracture temperature for the same mixture that included the same filler type as discussed earlier. As a result, the filler type has a significant effect on the average fracture temperature and fracture stress.

Table 7. Average fracture temperature and fracture stress of mixtures that include different filler types

Mixtures type	Fractural temperature, °C	Comments	Fractural stress, MPa
Binder PG	64-28		64-28
Dust	-31.5		2.94
	-31.1		3.10
	-28.1		1.57
Average	**-30.23**	Meet -28 °C	**2.54**
Lime	-28.3		3.54
	-27.9		3.27
	-26.8		2.92
Average	**-27.6**	0.4 °C warmer than -28 °C	**3.25**

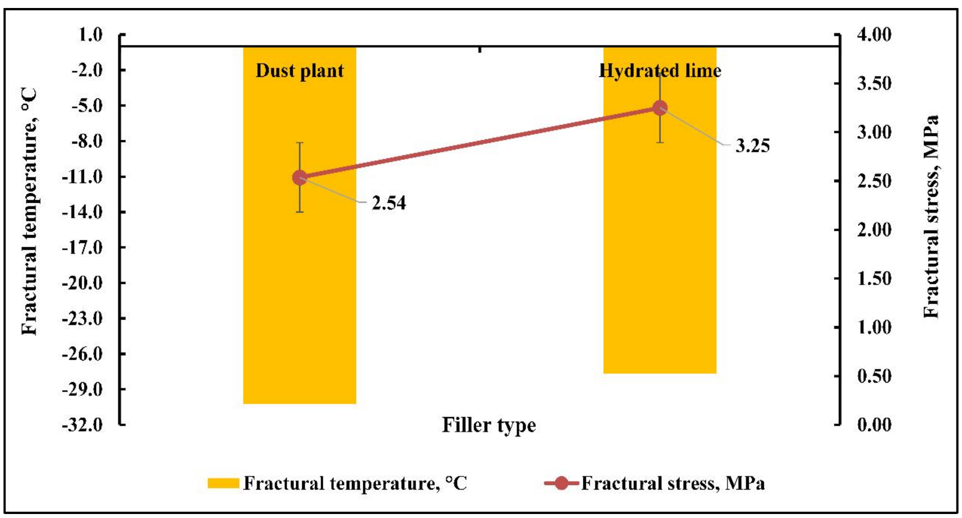

Figure 16. Fracture temperature and fracture stress of the mixtures that included different filler types

5.2.4. Effect of Filler on the Stiffness Modulus of Mixtures

The results of the dynamic modulus test are shown in Figure 17 and are presented as a complex modulus value (E*) versus the reduced frequency. It is noted that the mixture containing HL as a filler has a higher stiffness than the mixture containing DPt filler. These results highly correspond to the results of rutting and thermal cracks. The reason behind this was explained in the previous sections (5.2.2, 5.2.3).

Figure 18 shows the dynamic modulus values for all temperatures and frequencies used. Compared to the DPt addition, the addition of HL to a mixture would stiffen the mixture at the low and intermediate temperatures, temperatures ranging between −10 to 4 °C. This leads to a reduction in the cracking resistance of the mixture. In addition, the presence of hydrated lime as a filler significantly improved the elasticity of the asphalt mixture at higher temperatures, higher than or equal to 21°C. This is beneficial for the high-temperature performance.

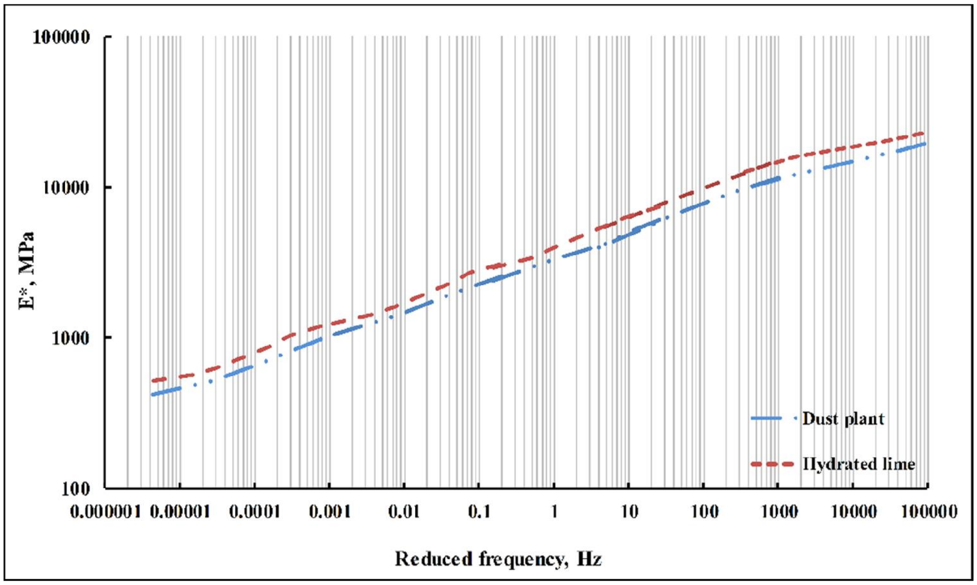

Figure 17. Master curve for asphalt mixtures with different filler types

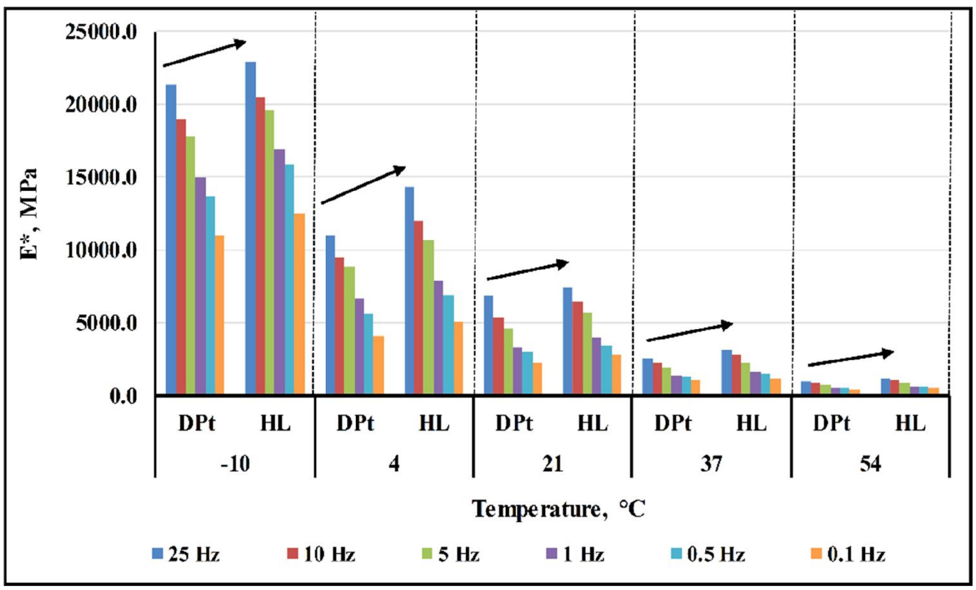

Figure 18. Dynamic modulus values for asphalt mixtures with different filler types at different temperatures and frequency

5.3. Field Performance Evaluation

In assessing potential field performance of incorporating 2.5% of HL and DPt in the asphalt mix, the Aashtoware software was utilized. This software applies the mechanical-empirical design method in designing road pavements and considers the influence of material properties, climate and traffic to determine future performance of designed pavements [40].

The design incorporated both level 1 and level 3 inputs. Level 1 input refers to actual laboratory measured properties of materials being incorporated within the pavement layer designs, while level 3 inputs are typical properties for materials being incorporated within the pavement structure in Ontario. These typical values (level 3) have been obtained from work performed by Applied Research Associate [41]. The pavement design utilized in this analysis is presented in Figure 19.

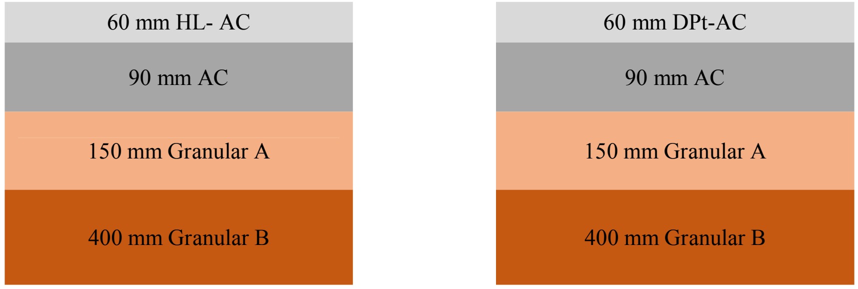

Figure 19. Pavement design for HL and DPt filler mixes

The design was for a major arterial road over a period of 25 years with an Average Annual Daily Truck Traffic (AADTT) of 5000 and climate region of Toronto, Ontario, Canada selected. The resilient modulus of the subgrade was 50 MPa signifying a moderate subgrade characteristic which has been identified as semi-infinite. The truck distribution was in accordance with typical values for major arterial roadways in Ontario as outlined in [41]. Also, the material properties for the 90mm AC layer, Granular A and Granular B layers were similar for both sections and in accordance with typical values as penned in [41] signifying level three input values in the Aashtoware software analysis. Actual laboratory measured values as already discussed above have been employed for the surface layer to differentiate both HL and DPt sections. These properties include dynamic modulus values at four different temperatures, air void content, effective binder content, Performance Grade (PG) properties. The Asphalt Concrete layers both have PG of 64-28.

The results are shown in Table 8. The outcomes reflect that over 25 years at 90% reliability, terminal IRI, permanent deformation and AC thermal cracking did not reach the target value to trigger maintenance and rehabilitation and so performed significantly better than expected for both sections. However, in terms of AC bottom - up fatigue cracking and top-down fatigue cracking, the target value was exceeded before the end of the design period. For the bottom-up fatigue cracks, the DPt section reached the target value by the 15th year, while the HL section by the 16th year. Hence, some maintenance and rehabilitation work required before this occurs. Generally, the HL section appears to perform better than the DPt sections with respect to all distress types except thermal cracking.

Table 8. Field pavement performance over a 25-year period

Distress Type	Target	Predicted	
		Dust Particle	Hydrated Lime
Terminal IRI (m/km)	3.00	2.96	2.94
Permanent Deformation - total pavement (mm)	10.00	7.52	7.40
AC bottom-up fatigue cracking (percent)	10.00	29.85	28.39
AC thermal cracking (m/km)	200.00	52.64	52.66
AC top-down fatigue cracking (m/km)	378.80	2586.53	2518.71
Permanent deformation -AC only (mm)	6.00	1.41	1.32

In terms of AC top-down cracking, the terminal value for the HL section was about three percent better than the DPt section. It further appears that the addition of HL could potentially reduce the permanent deformation that occurs on the AC layer compared with the addition of DPt. These results are consistent with laboratory results already presented.

6. Conclusions

The following conclusions can be drawn from all the testing and analysis performed on the application of various filler types in HMA in this study:

- The OAC for both filler types decrease when the filler percentage is increased. However, a significant decrease in the optimum asphalt binder content is observed when filler content is increased from 2.5 to 3% for both filler types.
- It is seen that an increase in filler content decreases VMA of the mixture for both filler types. A slight difference between two different filler types on the VMA property is noticeable. Compared to MTO specifications, the obtained results are higher than the required proportion.
- VFA values are proportionally reduced depending on an increase in the filler content. An insignificant variance between various filler effects on this volumetric property is found. Based on MTO requirements, it is indicated that the study findings are higher than the lower limit.

- Compared to other volumetric properties, Dp proportion behaves inversely for both filler types in which Dp proportion increases when the filler content is increased. The obtained values of Dp for the mix design with filler content 2% are unacceptable for both filler types due to lower values whereas the experimental values of Dp for mix design with filler content 2.5% and 3% were acceptable for both filler types based on the MTO specifications.
- Similar behaviour for the Gmm and Gmb properties with respect to different filler types with various proportions is observed. When the filler percentage increases, the values of Gmm and Gmb are increased for both filler types.
- The addition of filler of 2.5% is very successful for both filler types due to satisfying all MTO requirements for volumetric properties of HMA. Based on MTO specifications, the addition of 2.0% filler appears to be unsuccessful for both filler types due to lowering the dust to asphalt binder ratio. Mix design with 3.0% filler was also unsuccessful because of the lower value of OAC meaning that the mix is dry and there is insufficient asphalt binder to coat the aggregate particles.
- Filler type has a significant impact on the mechanical properties of HMA mixtures.
- The utilization of HL as a filler at 2.5 % demonstrated a significant improvement in mixture resistance to water, freezing, and thawing and has a higher cracking resistance than the DPt.
- TSR values from mixtures of both filler types are higher than the MTO requirement. This indicates that the mixtures that included both filler types have a good resistance to moisture damage. However, the addition of HL has a more pronounced influence on the moisture susceptibility characteristics than DPt filler.
- The use of HL in HMA mixtures leads to an increase in the mixtures ' stiffness, which is higher than DPt. This results in outstanding performance for HL mixtures due to a high resistance to permanent deformation.
- The mixtures with a DPt filler exhibit a considerable decrease in the average fracture temperature. Hence, this filler type appears to be highly successful in low-temperature regions.
- In terms of fracture stress, the mixture that included HL has a higher fracture stress than the mixture that included DPt filler, leading to a higher resistance to thermal cracks. However, this result is completely different than the average fracture temperature for the same mixture that included the same filler type.
- Predicted field performance results also reflect that HL filler mixes potentially could produce better performing pavements overtime than mixes incorporating DPt filler.

Including HL fillers within asphalt mixes is recommended to provide better performing mixes and longer lasting road pavements. Also, the outcomes of this study revealed that the utilization of filler, especially for HL at a proportion greater than 1%, is highly successful in asphalt pavement. Further study could explore the actual field performance of incorporating HL and DPt fillers through construction and instrumentation of a trial section.

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9. Conflicts of Interest

The authors declare no conflict of interest.

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