Evaluation of Warm Mix Asphalt Behaviour – Stability and Strength Perspective

Michael Esenwa, P.Eng.
Senior Pavement Engineer
McAsphalt Industries Limited
Scarborough, Ontario

J. Keith Davidson, P.Eng.
Director of Technology and Product Development
McAsphalt Industries Limited
Scarborough, Ontario

Anton S. Kucharek, P.Eng. C.Chem.
Director of Technical Services
McAsphalt Industries Limited
Scarborough, Ontario

ABSTRACT

The properties of warm mix asphalt such as indirect tensile strength, rutting, moisture susceptibility, stability and flow, etc. in comparison to hot mix asphalt properties are some of the primary concerns of the paving industry. Additionally, the curing times and aging behaviour of warm mix asphalt have unknown effects on the mixture properties.

The compatibility with current construction practices and equipment, compatibility with polymer binder, compatibility with Reclaimed Asphalt Pavements (RAP), etc. are some of the immediate concerns with warm mix asphalt. Some studies have been conducted to address some of these issues but are inconclusive, there is the need for more work and data to shade more light in this area.

This paper gives an in-depth laboratory study of various factors affecting warm mix asphalt mixture behaviour as it relates to stability and strength, focusing on determining the effects of mixing, compaction and conditioning temperature on volumetric properties, the indirect tensile strength, tensile strength ratio and rutting potentials of the mixture. It also looks at the aging characteristics of warm asphalt mixtures to understanding how it affects their properties.

RÉSUMÉ

Les propriétés des enrobés bitumineux tièdes comme la traction indirecte, l'orniérage, la susceptibilité à l'humidité, la stabilité et le fluage, etc. par rapport aux propriétés des enrobés à chaud sont quelques-unes des principales préoccupations de l'industrie du pavage. En outre, le comportement au mûrissement et au vieillissement des enrobés tièdes ont des effets inconnus sur les propriétés des enrobés.

La compatibilité avec les pratiques actuelles de la construction et l'équipement, la compatibilité avec le liant polymère, la compatibilité avec les enrobés bitumineux récupérés (RAP), etc. sont certaines des préoccupations immédiates avec les enrobés bitumineux tièdes. Certaines études ont été menées pour répondre à certaines de ces questions, mais ne sont pas concluantes, on a besoin de plus de travail et de données pour apporter un peu plus de lumière dans ce domaine.

Cet article donne une étude approfondie de laboratoire de divers facteurs affectant le comportement des enrobés bitumineux tièdes en ce qui concerne la stabilité et la force, en mettant l'accent sur la détermination des effets du malaxage, du compactage et du conditionnement de la température sur les propriétés volumétriques, la traction indirecte, le rapport de résistance à la traction et les potentiels à l'orniérage de l'enrobé. Il examine également les caractéristiques de vieillissement des enrobés bitumineux tièdes pour comprendre comment cela affecte leurs propriétés.

1.0 INTRODUCTION

The Marshall Stability (recorded in Newtons, N) of asphalt concrete pavement paving mixtures has been the most important property used by many agencies in ascertaining the ability of the paving mixture to resist shoving and rutting under traffic. In essence, the stability of a paving mixture should be high enough to handle traffic adequately, but not higher than the traffic conditions require; it has to be balanced, as a lack of stability will result in mixture rutting.

On the other hand, Marshall Flow is the ability of asphalt concrete paving mixture to adjust to gradual settlements and movements in the subgrade without cracking. Flow may be regarded as an opposite property to Stability as it determines the reversal behaviour of mixtures under traffic loading relating to its plastic and elastic properties. The Marshall Flow of asphalt concrete paving mixture is recorded in increments of 0.25mm. The calculated ratio of stability to flow represents an approximation of the ratio of load to deformation under particular test conditions, and can be used as a measure of the material's resistance to permanent deformation in service [1].

Moisture damage of asphalt mixes, commonly referred to as stripping, is a major distress affecting pavement performance. When the adhesive bond between asphalt cement and aggregates is loosened or weakened by the action of moisture, we say that stripping has occurred. The damaging effects that can result include rutting and cracking due to shear forces developed. The American Association of State and Highway Transportation Officials (AASHTO) T283 protocol has been used to detect moisture susceptibility mixes through the determination of a Tensile Strength Ratio (TSR) [2].

As Warm Mix Asphalt (WMA) technologies increase in usage due to their positive impacts and benefits, there have been questions raised about overall mix durability; user agencies want to increase their knowledge of how WMA affects both immediate and log-term performance asking the following questions: Will the asphalt cement binder be absorbed differently? Will fatigue life be increased since the aging effect is less? Will the mix be susceptible to moisture damage since the aggregate used in production of WMA is not super-dried as compared to Hot Mix Asphalt (HMA)? [3].

One important area that affects the pavement performance is mixture aging. When using WMA, we typically lower the production mixing temperature leading many to believe that there would still be moisture left in the mixture to induce damage. This laboratory study therefore looked at the aging characteristics of WMA to better understand how it affects their behaviour as it relates to stability and strength, focusing on determining the effects on density, stability and flow, TSR values and rutting potential [4].

2.0 MATERIALS AND EVALUATION PLAN

2.1 Materials

During plant production and placement in the field, WMA plate samples, bags of aggregates and cans of asphalt cement binder were retrieved and stored for testing as part of this study. The mix design used in this study was a typical 12.5mm nominal maximum size WMA produced with a Performance Graded (PG) 58-34P and placed on one of the regional highways in Ontario in the 2010 paving season. The job mix formula selected was a Ministry of Transportation Ontario (MTO) Category C Superpave Surface mix which typically is placed on routes with up to 3 million Equivalent Single Axle Loads (ESALs). The mix design was completed following the Superpave Volumetric Mixture Design Requirements.

To test the different mixtures for this study, individual materials in the same proportions as in the original mix design were prepared and batched according to the Asphalt Institute MS-2 [5] mix design test procedure replicating the plant produced mixture in the laboratory using McAsphalt PG 58-34P. The blend of aggregates and asphalt binder were then mixed in a mechanical mixer suitable to maintain the selected temperature. The warm mix technology selected was a chemical additive, which was added to the binder prior to mixing with the aggregate. Three mixes were used in this study; two mixes produced in the laboratory – Laboratory Control HMA and Laboratory WMA, as well as one plant produced WMA mixture (Plant WMA) sampled and stored during the paving operation. Each set of samples was prepared for testing.

Table 1 shows a summary of the mix design materials proportion and job mix formulae as it relates to this study.

Table1. Superpave 12.5mm Mix Design Information

Job Mix Formula Blend	**Materials**	
	Source	**Percentages (%)**
HL3 Stone	Carden	40.3
Asphalt Sand	CBM	9813.0
Screenings	Dufferin	26.7
Recycled Asphalt Pavement	Whitby	20.0
PG 58-34P Evotherm	McAsphalt	4.70
Superpave Volumetric Properties		
Parameter	**Specification**	**Selected**
Traffic category	C	C
G_{mm} @ N-Initial (%)	≤ 89.0	89.0
G_{mm} @ N-Design (%)	96.0	96
G_{mm} @ N-Maximum (%)	≥ 98.0	96.5
Air Voids (%)	4.0	4.0
Voids in Mineral Aggregate (%)	14.0 min.	14.8
Tensile Strength Ratio (%)	80.0 min	82.5
Bulk Relative Density (kg/m3)	2.421	
Maximum Relative Density (kg/m3)	2.525	

Note: OPSS is Ontario Provincial Standards and Specifications
PG is Performance Grade
Gmm is maximum Theoretical Specific Gravity of Mixture

2.2 Evaluation Plan

In order to achieve the objectives of this study, a test plan was developed as shown in Figure 1 and the evaluation was performed in five levels as follows:

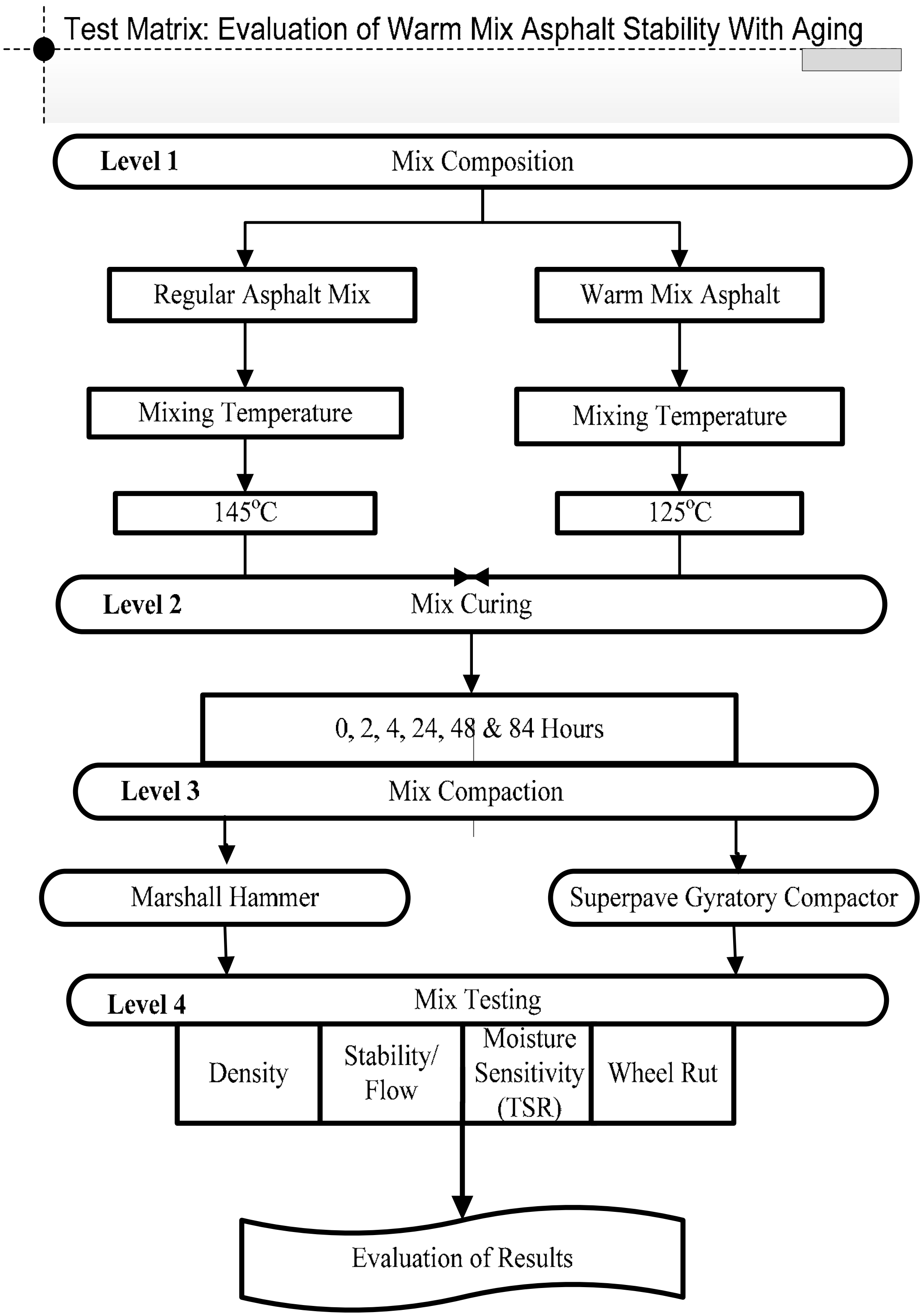

Figure 1. Evaluation Matrix

Level 1: Define Mixture composition:

- Plant Produced WMA
- Laboratory HMA Control Mixture
- Laboratory WAM Mixture

Level 2: Mixing and Curing temperature is defined for all mixtures:

- 145°C for Mixing HMA and 135°C for Short-term Curing
- 125°C for Mixing WMA and 115°C for Short-term Curing

Level 3: Compaction is performed for test samples

- With Superpave Gyratory Compactor
- With the Marshall Hammer

Level 4: Test is performed on Samples

- Bulk Density
- Marshall Properties
- Wheel Tut Test
- Moisture Sensitivity

Level 5: Analysis of Test Results

2.3 Specimen Preparation

The mixture was replicated in the laboratory utilizing a mechanical mixer that would produce a uniform consistent mix maintaining the desired mixing temperature while ensuring that all aggregates were properly coated. All materials were prepared by heating them to a constant mass at the respective mixing temperature before introducing them into the mixer. The warm mix additive was stirred with the asphalt binder properly to ensure it was dispersed before mixing with the aggregates.

A mixing temperature of 145^0C was selected for the PG 58-34P HMA control mixture and temperature of 125^0C was selected for the WMA mixture. In order to evaluate the effects of aging upon the properties of the mixtures under study, five aging periods were selected.

For the Superpave specimen, the mixtures where compacted at the specified number of gyrations. The compactive effort was determined by the number of ESALs anticipated on the pavement over a 20-year period. An angle of gyration of 1.25 was then applied to the specimen and compaction proceeded to the design number of gyrations – 75 in this case. After cooling, the specimens were extruded from the molds as shown in Figure 2.

Marshall specimens were fabricated following the same procedures for batching and mixing as for the Superpave specimens but compaction was completed using the Marshall hammer delivering 75 blows per side.

Curing of the loose mix was carried out in a forced draft oven at each mix compaction temperature according to AASHTO PP2 [6]. The mixture placed in a shallow pan was stirred every hour for the duration of the curing time prescribed. The HMA specimen loose mixtures were placed at a temperature of 135°C and 100°C for short and long term, respectively while 115°C and 80°C were used for the WMA. For all mixtures, aging times selected were 2, 4, 8, 24 and 84 hours.

Figure 2. Prepared Test Specimens

Compaction was performed according to desired methods; Marshall Compaction at 75 blows per side to produce specimens for Bulk Density, Air Voids, Marshall Stability and Flow tests and Superpave Gyratory Compaction set at required number of gyrations to produce specimens at 7.0% air voids for Tensile Strength Ratio (TSR) and Rut Tests. The plant produced WMA sampled from the November 2010 project was re-heated and compacted at 135°C following same steps mentioned above.

3.0 RESULTS AND DISCUSSION

3.1 Mixture Densification

One of the concerns with using WMA mixes is whether the increased workability will remain in the mix after the construction stage thereby allowing continued densification during the first years of service as compared to HMA mixes. Continued densification on the road may lead to some premature distresses such as bleeding, distortion, or rutting. In order to evaluate the level of densification of the three mixes, bulk densities and air voids content were determined after each aging period as shown in Figure 3.

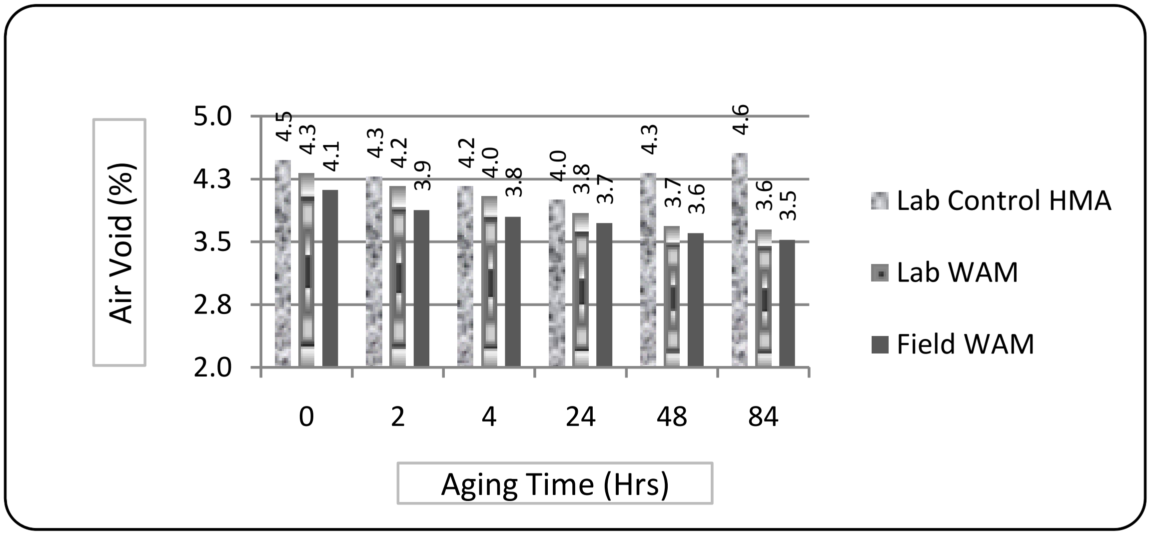

Figure 3. Mixture Air Voids vs. Aging Time

The effect of curing on both HMA and WMA was compared between the specimens compacted with the Marshal hammer, this was done in order to determine whether curing has a different effect on these mixes. The compaction result shows that the number of air voids has a slight tendency to decrease with longer curing time.

The bulk density of samples prepared at different curing temperature with the Marshall hammer was determined according to Ministry of Transportation Ontario LS262 procedure [**7**] and plotted in Figure 4.

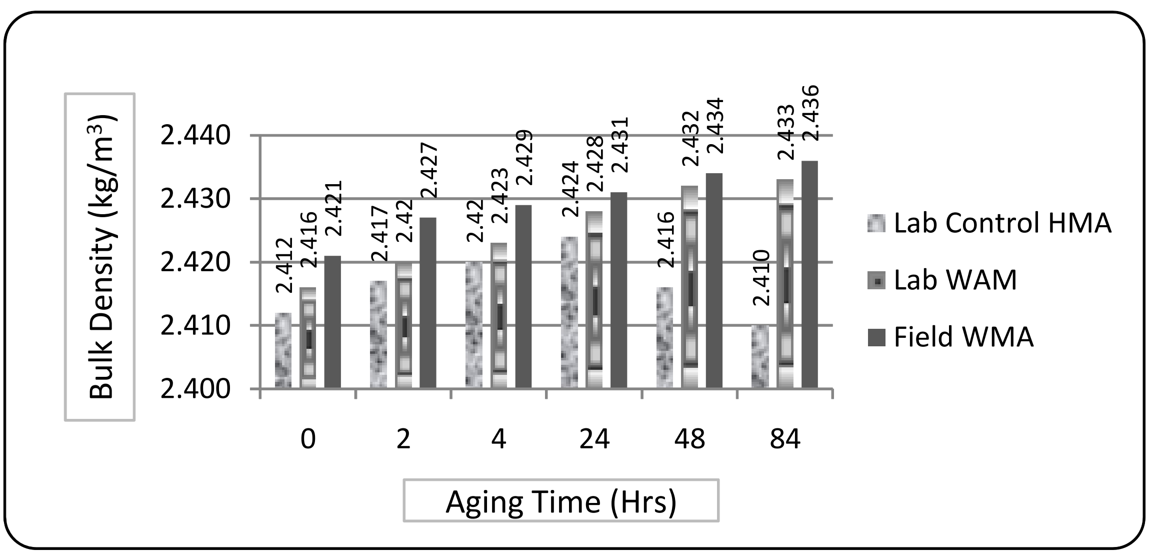

Figure 4. Mixture Bulk Density vs. Aging Time

The results indicate that numerically the difference between all WMA specimens and the HMA specimens is minor after short-term aging but when the mixtures were taken through long-term aging up to 48 hour and above the HMA specimen density decreased, this could be attributed to differences in oxidation hardening between HMA and WMA.

The final results in Figure 4 show an increase in density for all curing periods, the void content of the HMA has increased significantly and shows a large difference from all other results. After four hours of curing, the HMA had hardened further while the WMA had almost the same characteristics as densification continued. It must be noted that the HMA was cured at a higher temperature therefore the hardening probably had higher effect than for the WMA, which explains the further hardening of HMA after 24 hour period.

The gyratory compactor also allows an illustration of how the density of the asphalt mixture increases with increasing number of gyrations. The compaction in percent of maximum density for all three products under study at the chosen compaction temperature is as shown in Figure 5.

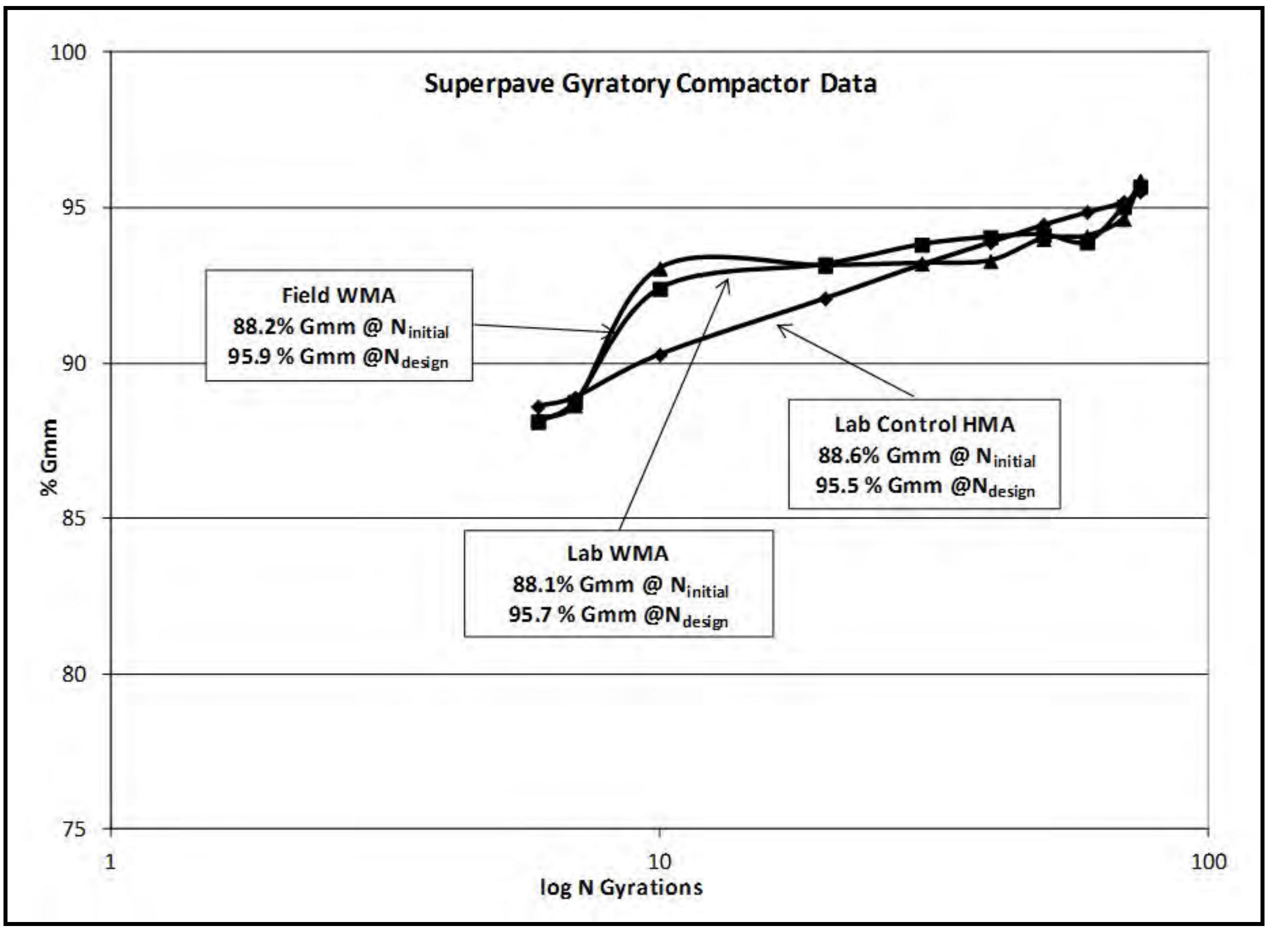

Figure 5. Densification Chart

The results show that the density at the designed compactive effort met the requirements for all samples. The initial compaction (N_{ini}) levels are within specification range. The densification of both WMA products had different characteristics; the density at the first stage of compaction was significantly higher than for the control HMA sample and reaches its final compaction at about 70 gyrations. At this point the density remains almost the same despite continuation to the required 75 gyrations for the mix design.

It should be noted that the compaction method itself can be important for asphalt mixes to simulate actual field compaction. The final density and mechanical characteristics for each type of mix depends on the aggregate orientation and the interlocking of the mineral skeleton.

3.2 Stability and Flow

Resistance to permanent deformation assessed according to Ministry of Transportation Ontario LS 263 [8] to compare Marshall Stability and Flow of the control HMA and WMA mixtures. All mixes were cured at the various curing times and compacted, then immersed in a water bath maintained at 60 ± 1^{o}C temperature for 30 minutes. The specimens were removed from the water bath and placed in the breaking head and placed on the testing machine (Figure 6).

Figure 6. Mixture Stability Test Machine

The load is applied to the specimen at a constant rate by the Marshall testing machine head until the maximum load is reached (the Marshall Stability value) at the measured displacement (the Flow value). The Marshall Stability and Flow values for each specimen are shown in Figures 7 and 8, respectively.

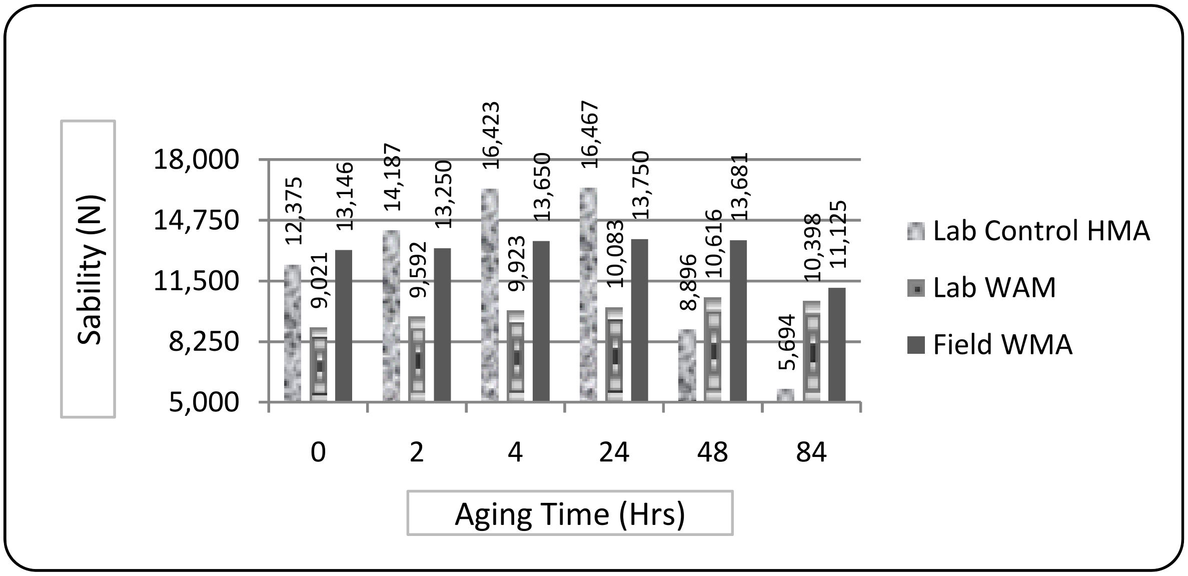

Figure 7. Mixture Stability vs. Aging Time

The results show a tendency to increase as the aging period increases for all the mixes and continue for the two WMA mixes all through up to 48 hour when they experience a slight reduction in stability value. This effect was also observed with the HMA mixture, but its peak stability occurred with specimens prepared with HMA cured for 24 hours. The loss of stability at the 48hour period was massive for the HMA specimen, only retaining half of its stability at the 24-hour aging period.

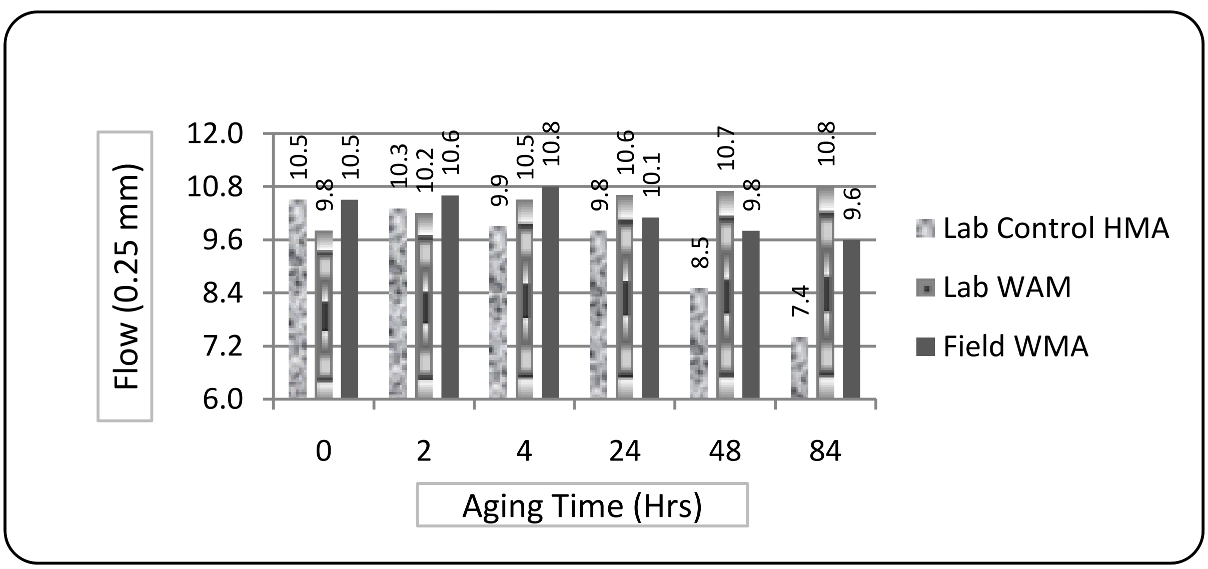

Figure 8. Mixture Flow vs. Aging Time

The flow can be considered as an opposite property to stability and the results again show a tendency to decrease with longer aging periods, particularly for the HMA.

Rutting Susceptibility testing completed in this research was based on the PTI Asphalt Pavement Analyzer following the guidelines for Standard Test Method for Determining Rutting Susceptibility of Asphalt Paving Mixtures using the Asphalt Pavement Analyzer (AASHTO) procedure TP 63-07 [**9**]. The APA is a multifunctional loaded wheel tester that uses pneumatic cylinders on a concave metal wheel to apply a repetitive load through a pressurized rubber hose to the specimens. Samples were conditioned for a minimum of 6 hrs at 58°C before testing with a wheel load of 445 ± 22N and air pressure of 700 ± 35kPa and the average of the rut depths for the specific mixture are then measured at 8000 cycles.

Figure 9 shows a summary of rut depths for each mix under study. A closer look shows that the Laboratory HMA samples had an average rut depth of 5.4mm, while the WMA rut resistance increased as the aging time increased and averaged 8.4mm. Field produced WMA had a less rut depth compared to the two Laboratory mixes with an average of 2.5mm; an indication of increased strength gain after long period of storage at room temperature.

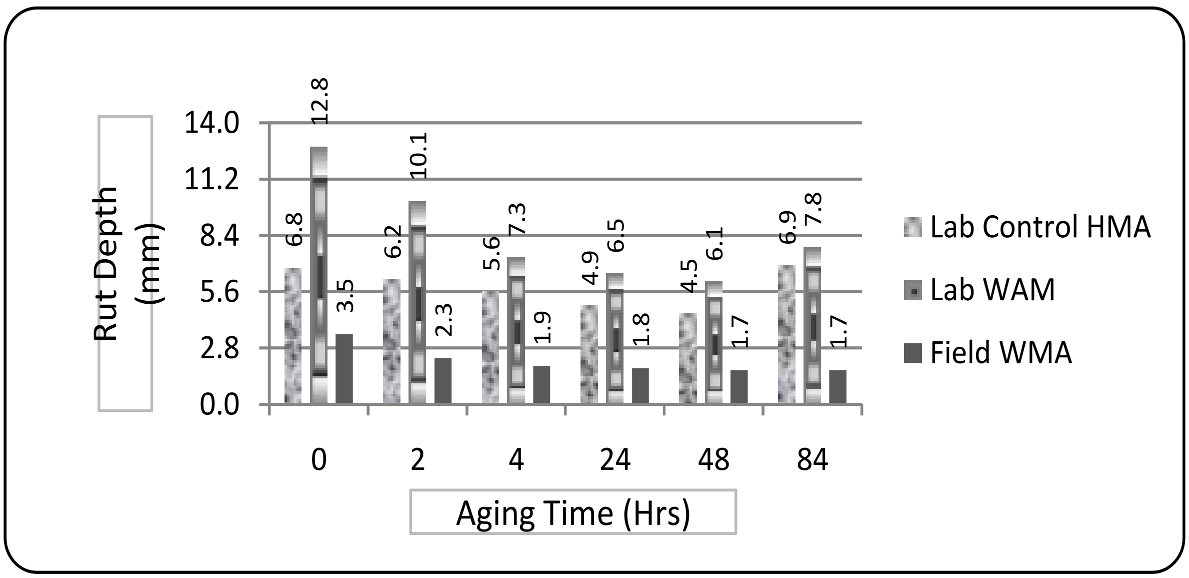

Figure 9. Mixture Rut Depth vs. Aging Time

3.3 Moisture Susceptibility

The next step in this study plan was to evaluate the moisture susceptibility of the mixtures. This was accomplished by performing test method AASHTO T283, Resistance of Compacted Bituminous Mixtures to Moisture Induced Damage [2] on the design aggregate blend at the design asphalt binder content. Test specimens were compacted to 7% air voids ±0.5%. One subset, consisting of three specimens, was considered the control set. The other subsets of three specimens were conditioned. These specimens are subjected to partial vacuum saturation followed by a freeze cycle and then followed by a 24-hour thaw cycle at 60 C. The ratio of conditioned to unconditioned tensile strength is called the Tensile Strength Ratio (TSR) and the results are provided in Figure 10.

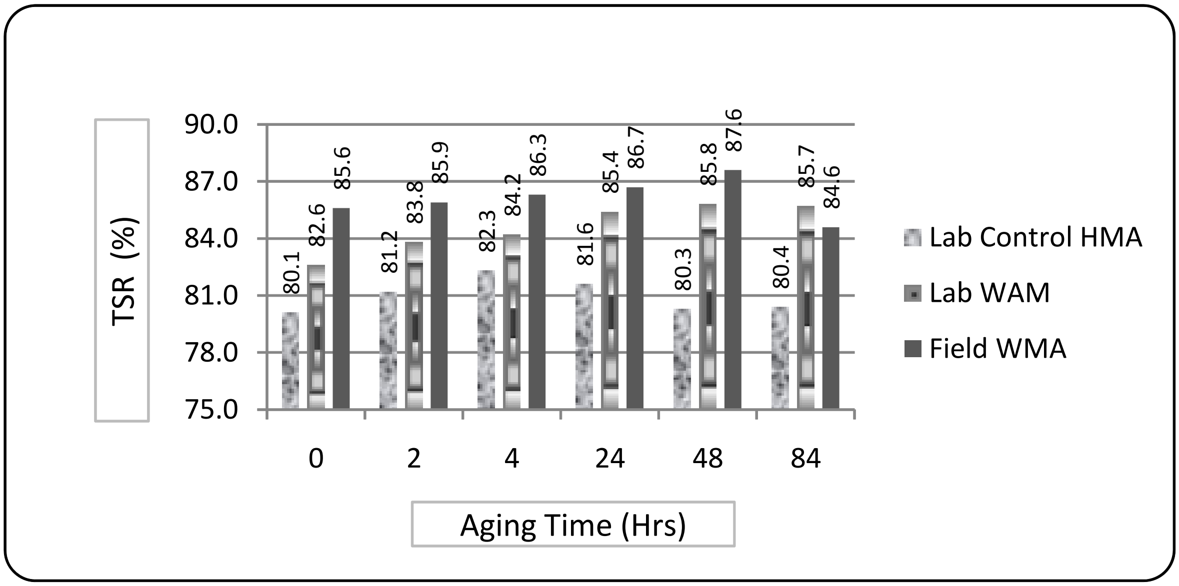

Figure 10. Mixture TSR vs. Aging Time

The Ministry of Transportation Ontario criterion for TSR is 80%, minimum. The Laboratory HMA control mixture was dosed with 0.25 percent anti-stripping agent after the initial trial failed to meet specification requirement. The Laboratory WAM did not require any anti-stripping additive. All TSR values meet minimum passing criteria but the TSR values for the WMA are lower than the HMA with one exception; the initial HMA without anti-stripping agent failed, but passed after being treated.

Table 2. Summary of Test Results before Aging

Results Prior to Aging	Laboratory Control HMA	Laboratory WMA	Field WMA	Field WMA
Investigated Properties			Jan – Mar 2011	Oct – Nov 2010 (Average)
Bulk Relative Density (kg/m^3)	2.412	2.416	2.421	2.420
Air Voids (%)	4.5	4.3	4.1	3.7
Stability (N)	12,375	9,021	13,146	Not Available
Flow (0.25mm)	10.5	9.8	10.5	
Tensile Strength Ratio (%)	80.1	82.6	85.6	80.5
Rut Depth (mm)	6.8	12.8	3.5	Not Available

Note: WMA and HMA are Warm Mix Asphalt and Hot Mix Asphalt, respectively

Based on a minimum TSR requirement of 80%, the conventional HMA, the Laboratory and Field WMA mixtures are not moisture susceptible; however the HMA mixture passed the TSR test after dosage with anti-stripping additive. The TSR values increased as the aging time increased and the WMA performed well above the 80% requirement.

Table 3. Summary of Test Results after Aging

Results Prior to Aging Investigated Properties	Laboratory Control HMA	Laboratory WMA	Field WMA
Bulk Relative Density (kg/m^3)	2.420	2.423	2.429
Air Voids (%)	4.3	4.0	3.8
Stability (N)	14,187	9,921	13,650
Flow (0.25mm)	10.3	10.5	10.8
Tensile Strength Ratio (%)	81.2	84.2	86.3
Rut Depth (mm)	6.2	7.3	1.9

Note: WMA and HMA are Warm Mix Asphalt and Hot Mix Asphalt, respectively

4.0 SUMMARY OF FINDINGS

From the testing and findings of the study of the WMA and the HMA control mix, the following conclusions are drawn.

1. Curing before carrying out compaction of WMA in the laboratory is essential to provide adequate test results. Oxidation hardening due to production and compaction temperature and use of WMA chemical additive technology had a noticeable effect on the WMA mixtures. Therefore, the curing time makes it possible to simulate initial strength gain that would occur in the actual field conditions.

2. A stability increase with extended curing time indicates that WMA mixtures incorporating a chemical process are much more workable and less oxidized than HMA mixes since they continue gaining strength for a longer aging period. The mixtures are also highly resistant to permanent deformation, indicating less rutting potential with time as the mixtures age. Although the flow value for WMA and the control HMA is relatively close, higher stability was gained over time by the WMA mixes thereby indicating higher stiffness over time with greater ability to spread the applied load.

3. Densification data showed contrasting evidence for the WMA and HMA mixtures as the differences in density for the WMA and HMA was small in all cases. This suggests that the use of a WMA chemical process products allows a continuous but stable densification process with increase in aging time and requires less compaction effort to achieve same density and with application of further compaction, higher density can be achieved as the WMA mixture remains workable over greater time than the HMA mixture.

4. The effects of aging and curing time on the moisture susceptibility of the WMA and HMA control mixtures were evaluated, based on the data collected the mixtures moisture susceptibility performance improved significantly as the aging time increased, mixtures cured for a longer time exhibited the best performance. Data collected after the initial curing period of the specimen for two hours was performed in context of this research and has shown that longer curing for WMA is necessary than for HMA.

It is important to mention that this is an initial study and that more testing is required over a wider range of WMA mixes with different process technologies.

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