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# Comparative Evaluation of WMA Additives Effects on Conventional and Polymer Modified Asphalt Pavements

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## Abstract

This study is mainly focused on the evaluation of the effect of Warm Mix Asphalt (WMA) additives on the performance grade of straight and polymer modified asphalt binder and the performance of asphalt mixtures. In order to analyze these effects, the Performance Grade (PG) of asphalt binder and the degree of compaction of WMA mixtures with various additives were examined initially. Moreover, the degree of compaction was evaluated in field test sections. Lastly, the effect on WMA performance were evaluated using wheel tracking test and indirect tensile (IDT) strength test for the rutting resistance, moisture susceptibility and crack resistance, respectively. Based on the laboratory and field test results, it can be concluded that WMA additives can affect the PG grades of conventional but not for polymer modified asphalt binder while viscosity related to mixing and compaction results in conversely. From the field test, the rutting and crack resistances of WMA pavements are higher than HMA pavements in most cases.

Keywords: *warm mix asphalt, performance grade, degree of compaction, moisture susceptibility, rutting, fatigue*

## 1. Introduction

A great need and interest for Warm Mix Asphalt (WMA) techniques has been rapidly increasing because of its lower energy consumption, lower environmental impact, and extended construction season compared to conventional Hot Mix Asphalt (HMA). Warm mix asphalt has an opportunity for the asphalt industry to improve its product performance, construction efficiency and environmental stewardship. Based on the study of M.C. Rubio *et al.* (2012), the performance characteristics of WMA mix can be at least equivalent to conventional mixtures. This is possible because of often better workability and hence better compaction which can be achieved by using warm mix asphalt.

A variety of WMA additives has been developed basically to enhance WMA pavement compaction and workability at relatively lower temperature during mixing and construction. The additives decrease the viscosity of binder or reduce the internal friction between the aggregate particles without change of binder viscosity (FHWA, 2012). According to You *et al*. (2008) and Zaumanis (2008), the temperature reduction function of WMA resulted from the technologies of organic and chemical additives, and foaming processes based on water. However, in spite of their different types of technologies, they have the same targets which are lower viscosity, better workability, and emission conditions. Al-Rawashdeh (2008) also suggested that benefits of paving related to WMA technologies enhance the workability and compaction of the mix since WMA acts as a compaction aid and reduces the compaction effort required. From the study of the Use of Warm Mix Asphalt (EAPA, 2010), mixtures are produced and paved at lower temperatures than HMA. This temperature reduction of 20-40°C has led to the following temperature based classification of asphalt mixtures: Hot Mix Asphalt or HMA (190-150°C), Warm mix asphalt or WMA (100-140°C), half-warm mix asphalt or HWMA (60-100°C) and cold mixtures (0-4°C).

With respect to its low working temperature, a decrease of 30 °C in mixing temperature of WMA was still observed by Rondon-Quintana *et al*. (2016) by adding certain additive HUSIL (1%) which also improved workability and improved binder stiffness and resilient modulus. Same observation was made by Pereira *et al* in which 1% application of a certain additive can reduce compaction temperature of WMA up to 50°C. Moreover, recent studies show the promising performance of WMA with additives. Wahjuningsih *et al.* (2017) found that 15% BNA-R additives greatly improved the permanent deformation (damage groove) performance of WMA. Meanwhile, Oner *et al.* observed an improved rutting performance of WMA with 4% SBS copolymer. An addition of organic and chemical additives can decrease penetration values of Polymer Modified Binder (PMB) mixtures. However, based on the present study of the same authors, an

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optimum additive content must be used for certain compaction temperature and WMA for optimum pavement performance.

Three types of WMA techniques are commonly used: Organic wax, chemical additives, and foaming agents. Organic waxes such as Sasobit® and foaming agents such as Aspha-Min® serve as a surface-active agent that reduces effective viscosity of asphalt binder. On the other hand, Evotherm™ is one type of chemical additives that reduces friction at the interface between aggregates and asphalt binder. Since it has been well known that WMA additives help the mixture be compacted at relatively lower temperature, degree of compaction of WMA pavements must be evaluated further to analyze the effects of WMA additives after the PG of asphalt binder modified by different WMA additive.

According to an NCAT report by Gudimettla *et al.* (2003), the compaction of asphalt mixtures depend on asphalt binder viscosity and aggregate properties such as type, angularity, nominal aggregate size, and gradation. In this study, all the conditions of WMA were the same except for the viscosity or PG of the asphalt binder due to the addition of WMA additives. Based on the SUPERPAVE mix design manual documents (SHRP-A-407, 1994), the range of mixing and compaction temperature in laboratory depends on the viscosity of asphalt binder. The viscosity was measured by a Saybolt-Furol viscometer which is used for liquids. In order to measure the kinematic viscosity more efficiently, the viscosity measurement unit of asphalt binder was then changed from Saybolt-Furol to centistokes (cSt). SUPERPAVE also has the same fundamental concept with the Saybolt-Furol method but the measurement unit, Pascal-seconds (Pa-s) is changed from cSt. However, no method can be applied to polymer-modified binders because they need to be heated up to unreasonably high temperature to obtain the same viscosity of the unmodified asphalt binder.

There are a variety of mixture design methods for HMA mixtures. According to the study of Zaumanis (2010), the SUPERPAVE design is widely implemented in the USA whereas in Europe the most common design method is the Marshall method. According to Von Devivere *et al.* (2010), both have been used to test WMA technologies as well. Furthermore, WMA processes have also been tested with many different types of asphalt materials (dense graded, stone mastic, porous, and mastic asphalt). Based on this research, there are no restrictions on the use of traditional design methods for WMA.

Yildirim *et al.* (2000) suggested that traditional methods for deciding the mixing and compaction temperature are not proper for modified asphalt binders. Hence they tried to resolve this limitation by estimating viscosity at its shear rates. De Sombre *et al.* (1998) proposed compaction temperature for HMA which is similar to the behavior of soil by using Mohr-Coulomb model to describe the shear stress in mixture. From this study, it was concluded that the main cause affecting the degree of compaction of the WMA was the viscosity of asphalt binder.

In a study conducted by Bennert *et al.* (2010), the Marshall compactor was recommended to evaluate the degree of compaction of asphalt mixtures in addition to an asphalt lubricity tester and asphalt workability device. It was also mentioned that a gyratory compactor was not proper for the evaluation of degree of compaction because this equipment is commonly insensitive to workability and compaction. On the other hand, the Marshall compactor was considered to be the best tool to evaluate workability and degree of compaction. Hence, this study used the Marshall Compaction method for the evaluation of the laboratory degree of compaction of the WMA at a variety of temperature.

## 2. Objectives

The main objective of this study is to examine the effect of WMA additives on the performance grade of asphalt binder and to evaluate the degree of compaction and performance of the WMA mixtures using laboratory tests.

## 3. Experimental Program

### 3.1 Materials

#### 3.1.1 Asphalt Mixtures

This study used dense graded asphalt mixtures with a 19-mm Nominal Maximum Aggregate (NMAS) normally used as wearing surface in Korea. The particle size distribution of the aggregates is shown in Fig. 1. Two types of asphalt binder were used in the asphalt mixtures: Straight asphalt binder with Performance Graded (PG) 64-16 and polymer modified asphalt binder of PG 76-22, named as HMA and PMA, respectively. Optimal asphalt binder contents (OAC) of 4.8% and 5.0% were determined for HMA and PMA, respectively using the Marshall Mix design procedure (ASTM D1559, 1989; AASHTO T 245, 1997). WMA mixtures consisted of the same components of the HMA or PMA mixtures except for the WMA additives.

#### 3.1.2 Warm Mix Asphalt Additives

Five types of WMA additives were used in this study: LEADCAP-

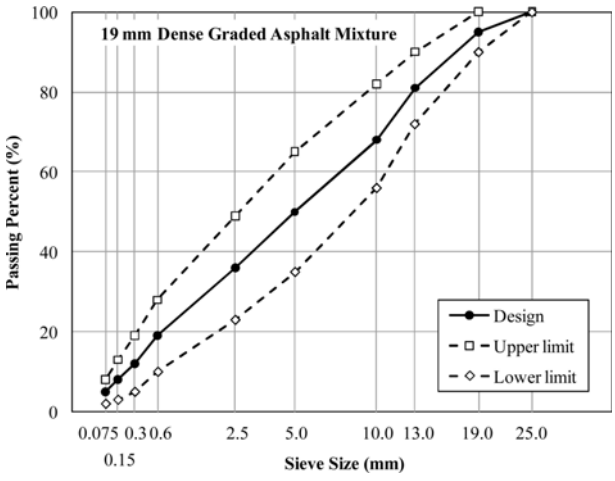


Fig. 1. Aggregate Gradation of the Asphalt Mixtures

Table 1. Characteristics of WMA Mixtures and Additives

| Asphalt Binder Grade | Mix ID | | WMA Additives | | | Optimum Asphalt Content (%) |
|---|---|---|---|---|---|---|
| | | | Name | Type | Content (%) | |
| PG 64-16 | WMA | A | LEADCAP-c64 | Organic | 3.0 | 4.8 |
| | | B | Sasobit | Organic | 1.5 | |
| | | C | PBSW | Organic | 4.0 | |
| | | D | SMRA | Organic | 0.5 | |
| | | E | Densicryl | Chemical | 0.5 | |
| PG 76-22 | WMA | PA | LEADCAP-c76 | Organic | 3.5* | 4.9 |
| | | PB | Sasobit | Organic | 1.5** | |
| | | PC | PBSW | Organic | 3.0 | |

*0.5% of polymer modifier was additionally added.
**3.0% of polymer modifier was additionally added.

Table 2. Test Configurations of Laboratory Tests for the HMA and WMA

| Material | Test | Material Property | Condition | Specification |
|---|---|---|---|---|
| Asphalt binder | Cleveland Open Cup | Flash point | | ASTM D92 |
| | Rotational Viscosity | Viscosity | 135°C | ASTM D4402 |
| | DSR | G*, δ | 22 ~ 82°C | ASTM D7175 |
| | BBR | Creep stiffness, m-value | -6, -12°C | ASTM D6648 |
| | Penetration | Penetration | 25°C | ASTM D5 |
| | RTFO | Short-term aging | | ASTM D2872 |
| | PAV | Long-term aging | | ASTM D6521 |
| Mixture | Marshall Compaction | Air Voids | 90~160°C | ASTM D1559 |
| | Wheel Tracking | Rut Depth | 60°C | AASHTO TP 63 |
| | IDT Strength | Toughness | 0, -10°C | AASHTO TP 9 |
| | IDT Strength | TSR | Dry, Wet | ASTM D4867 |

c64, Sasobit, PBSW, SMRA and Densicryl. Corresponding WMA mixtures were named as WMA-A, WMA-B, WMA-C, WMA-D, and WMA-E, respectively. In addition, three types of WMA additives of LEADCAP-c76, Sasobit, and PBSW were used for the PMA mixtures and corresponding WMA mixtures were named as WMA-PA, WMA-PB, and WMA-PC, respectively. The WMA additives are an organic type except Densicryl which is a chemical type. Among the WMA additives, additives A, C, D, PA, and PC were developed in Korea. The contents of the WMA additives are summarized in Table 1. In this study, the WMA additives were not considered in mixture design so that the mixture design of the WMA mixtures was the same as original HMA and PMA mixtures, including aggregates distributions and OAC. Thus, the OAC of the WMA-A to E mixtures were 4.8% and the OAC of the WMA-PA to PC mixtures were 4.9%. The optimum WMA additive content was used as recommended by each manufacturer. Polymer modifier of 0.5% and 3.0% were added to the WMA-PA and WMA-PB mixtures, respectively to adjust the PG of the asphalt binder as PG 76-22.

### 3.2 Laboratory Tests

Physical and mechanical performance of asphalt binder can be altered when WMA additives are used. It has been assumed in the mix design of WMA mixtures that PG and OAC are not changed by the addition of WMA additives. For the appropriate usage and design of WMA, the effect of WMA additives on the PG of asphalt binder should be evaluated first. Several tests were conducted to measure the physical properties of original and modified asphalt binder with WMA additives and then the PG of the original and modified asphalt binder was determined. The DSR and BBR tests were conducted at various temperatures to determine the PG of the straight asphalt binder with WMA additives. The tests were also conducted at a specific temperature for the polymer modified asphalt binder with WMA additives to examine whether or not it can pass corresponding PG 76-22 requirements. Table 2 shows the laboratory tests conducted for the asphalt binder and mixtures with/without additives.

#### 3.2.1 Performance Grade Test

A series of laboratory tests were conducted to determine the PG of asphalt binder with and without the WMA additives. Dynamic Shear Rheometer (DSR) tests were conducted at various temperatures for original asphalt binder, Rolling Thin Film Oven (RTFO) residue, and pressure air vessel (PAV) residue. Bending Beam Rheometer (BBR) tests were conducted at -6 and -12°C for the PAV residue. The DSR and BBR tests were done at various temperatures for the asphalt binder used in the HMA mixtures to determine the PG of the asphalt binder. For the PMA and WMA-PA, PB, and PC, polymer modifiers were already added to asphalt binder so that it was examined whether or not it

can pass the PG 76-22 requirements. The Cleveland open cup test was done to determine flash point. Rotational Viscosity (RV) tests were conducted at 135°C to obtain viscosity of asphalt binder during compaction. Using the penetration test (ASTM D5, 2013), penetration was tested at 25°C which is the representative average temperature of asphalt binder in use.

#### 3.2.2 Compaction Test

The effect of the WMA additives on the compactability of the WMA mixtures was evaluated based on the air voids of the mixtures at various compaction temperatures. The Marshall Compaction method as recommended by Bernnert *et al.* (2010) was used to examine the degree of compaction and air voids of the asphalt mixtures. An appropriate compaction temperature of the WMA mixtures can be determined where the same air voids of the control HMA or PMA mixtures are achieved. Two types of sample preparation methods were used in the compaction tests: Laboratory-mixed and field-mixed mixtures. The laboratory-mixed mixtures were manufactured in a laboratory from mixing to compaction while field-mixed mixtures were manufactured with loose mixtures sampled from a construction site. The laboratory-mixed mixtures were subjected to 2 hours of short-term aging at a corresponding compaction temperature. For the field-mixed mixtures, the loose mixtures were reheated for 1.0 to 1.5 hours to achieve compaction temperature and compacted immediately. The target air voids of the laboratory-mixed mixtures were 4.0%, representing a long-term compaction condition. The target air voids of the field-mixed mixtures were 8.0% corresponding to an initial field construction condition. The number of blows in the Marshall Compaction was set to 75 by each side. Three specimens were prepared for the laboratory- and field-mixed mixtures each.

#### 3.2.3 Performance Test

Two performance tests were conducted to evaluate the performance of the WMA mixtures: A wheel tracking test in accordance to EN 12697-22 and KS F 2374 for rutting resistance and an indirect tension (IDT) strength test in accordance to ASTM D 6931 for crack resistance. For the wheel tracking test, a plate-shape specimen of 30 cm by 30 cm and 5 cm in thickness was manufactured by pneumatic roller compaction and a target air voids of the specimen was 4.0%. The wheel tracking test was conducted at 60°C. In addition, Tensile Strength Ratio (TSR) determined from the IDT tests is used to examine moisture susceptibility of the WMA mixtures.

### 3.3 Field Test

In addition to the laboratory compaction tests, the degree of field compaction was evaluated in six test sections where the WMA-A, -B, -C, -D, and -E mixtures were used and the HMA mixture was used as a control section. The test sections were constructed on September 16$^{th}$, 2010 in Seoul, Korea. A 5-cm-thick asphalt concrete layer was overlaid on an existing asphalt pavement. The number of passage of compaction equipment and compaction temperature was monitored during the construction. Mixing temperature at the field and initial compaction temperature were also monitored. The target mixing temperatures of the control HMA and WMA mixtures were adjusted to 170 ± 5°C and 140 ± 5°C, respectively. Herein, mixing temperature was raised by 10°C considering slightly lower air temperature of 15°C and strong winds at the construction site. Also, the target compaction temperatures of the HMA and WMA mixtures were 145°C and 115°C, respectively which are 25°C lower than corresponding mixing temperature. The minimum degree of compaction was 96%, bulk specific gravity ($G_{mb}$) ratio of a pavement core to a laboratory specimen manufactured with field-mixed mixtures. After the construction, three field cores of 100 mm in diameter were taken from each test section to measure $G_{mb}$ of the HMA and WMA pavements.

## 4. Results and Discussion

### 4.1 Performance Grade of WMA Binders

The control asphalt binders used in this study were straight and polymer modified asphalt binders (PMA). The effect of the WMA additives on the PG of the two types of asphalt binders was examined. The results of the laboratory tests to determine the PG of the asphalt binders with and without WMA additives were summarized in Tables 3 and 4. The PG of the straight asphalt binder was classified as PG 64-16 while it was expected to be PG 64-22. In Korea, penetration grading has been used more popularly than performance grading so that the PG of AP-5, penetrating grading of 60 to 80 at 25°C, does not match PG 64-22 occasionally. The PG of the PMA was classified as PG 76-22.

#### 4.1.1 Effect of WMA Additives on Performance Grade of Straight Asphalt Binder

The PG of the WMA-A and WMA-B binders was bumped up in high temperature from PG 64-XX to 70-XX. The PG of the WMA-A and WMA-E binders was bumped down in low temperature from PG XX-16 to XX-22. The PG of the WMA-C and WMA-D binders was the same as the PG of the control asphalt binder. Therefore, the addition of the WMA additives could affect the PG of the control in either high and/or low temperature. It indicates that the WMA additives can influence the performance of the WMA during mixing and compaction. In addition, it can be expected that the rutting resistance of the WMA-A and WMA-B mixtures and crack resistance of the WMA-A and WMA-E mixtures are better than other WMA mixtures.

It is well known that the viscosity at 135°C is related to mixing and compaction of asphalt mixtures. Due to the effect of WMA additives, the WMA binders were expected to have lower viscosity at 135°C than the control asphalt binder. The viscosity at 135°C of the WMA-C binder was 16.9% lower than that of the control asphalt binder. The WMA-A, WMA-D, and WMA-E binders had similar viscosity at 135°C to the control asphalt binder. However, the viscosity at 135°C of the WMA-B binder is

Table 3. PG Test Results of Straight Asphalt Binder with/without WMA Additives

| Parameter | T (°C) | HMA | WMA-A | WMA-B | WMA-C | WMA-D | WMA-E | Requirement |
|---|---|---|---|---|---|---|---|---|
| Tests on Original asphalt binder | | | | | | | | |
| Flash point (°C) | | 343 | 333 | 341 | 337 | 339 | 335 | Min. 230 |
| Penetration | 25 | 62.3 | 62.0 | 62.5 | 59.5 | 59.0 | 60.0 | 60 ~ 80 |
| Viscosity (Pa-s) | 135 | 0.415 | 0.385 | 0.715 | 0.345 | 0.435 | 0.400 | Max. 3.0 |
| DSR $G^*/\sin\delta$ (kPa) | 58 | 3.122 | - | - | 2.044 | 3.129 | 2.044 | Min. 1.0 |
| | 64 | 1.340 | - | - | 1.109 | 1.445 | 1.019 | |
| | 70 | *0.624* | 3.334 | 3.473 | *0.468* | *0.718* | *0.468* | |
| | 76 | *0.324* | 2.152 | 1.971 | *0.256* | *0.394* | *0.256* | |
| | 82 | - | 1.406 | 1.265 | - | - | - | |
| High Temp. PG | | **64** | 82 | 82 | **64** | **64** | **64** | |
| Tests on RTFO Residue | | | | | | | | |
| Mass Loss (%) | | 0.04 | 0.02 | 0.11 | 0.05 | 0.08 | 0.09 | Max. 1.0 |
| Residual Penetration (%) | | 56.9 | 71.9 | *51.7* | *50.4* | 67.7 | 58.0 | Min. 55 |
| DSR $G^*/\sin\delta$ (kPa) | 58 | 5.08 | - | - | - | 5.60 | - | Min 2.2 |
| | 64 | 2.24 | 5.47 | - | - | 2.50 | 3.28 | |
| | 70 | *1.05* | 2.77 | 4.31 | - | *1.18* | *1.52* | |
| | 76 | *0.53* | - | *2.16* | 5.91 | *0.56* | *0.74* | |
| | 82 | - | - | *1.19* | 3.76 | - | - | |
| High Temp. PG | | **64** | **70** | **70** | 82 | **64** | **64** | |
| Tests on PAV Residue | | | | | | | | |
| DSR $G^*\sin\delta$ (kPa) | 25 | *5805* | *6311* | *7293* | *6356* | - | 3135 | Max. 5000 |
| | 28 | 4058 | 4431 | *5349* | 4522 | 4363 | 2032 | |
| | 31 | - | - | 3983 | - | 3118 | 1292 | |
| | 34 | - | - | 2945 | - | 2200 | - | |
| | 37 | - | - | - | - | 1529 | - | |
| Low Temp. PG | | **-16** | **-22** | **-16** | **-16** | **-16** | **-22** | . |
| BBR, Creep Stiffness (MPa) | -6 | - | - | 159.5 | - | - | - | Max. 300 |
| | -12 | 203.9 | 219.9 | 256.5 | 221.3 | 245.9 | 216.8 | |
| Low Temp. PG | | -22 | **-22** | -22 | -22 | -22 | **-22** | |
| BBR m-value | -6 | - | - | 0.331 | - | - | - | Min. 0.3 |
| | -12 | 0.318 | 0.307 | *0.281* | 0.305 | 0.319 | 0.309 | |
| Low Temp, PG | | -22 | **-22** | **-16** | -22 | -22 | **-22** | |
| Final PG | | **64-16** | **70-22** | **70-16** | **64-16** | **64-16** | **64-22** | |

Table 4. PG Test Results of Polymer Modified Asphalt Binder with/without WMA Additives

| Parameter | T (°C) | PMA | WMA-PA | WMA-PB | WMA-PC | Requirement |
|---|---|---|---|---|---|---|
| Tests on Original asphalt binder | | | | | | |
| Penetration | 25 | 63 | 29 | 35 | - | 60~80 |
| Viscosity (Pa-s) | 135 | 3.715 | 0.638 | 1.037 | - | Max. 3.0 |
| DSR, $G^*/\sin\delta$ (kPa) | 76 | 1.75 | 2.28 | 1.81 | 1.68 | Min. 1.0 |
| Tests on RTFO Residue | | | | | | |
| Mass Loss (%) | | 0.1 | 0.37 | -0.09 | - | Max. 1.0 |
| Residual Penetration (%) | | - | 63.0 | 68.6 | - | Min. 55 |
| DSR, $G^*/\sin\delta$ (kPa) | 76 | 2.54 | 2.39 | 3.69 | 2.26 | Min. 2.2 |
| Tests on PAV Residue | | | | | | |
| DSR, $G^*\sin\delta$ (kPa) | 31 | 2760 | 1480 | 2760 | 1770 | Max. 5000 |
| BBR, Creep Stiffness (MPa) | -12 | 158 | 191 | 249 | 26 | Max. 300 |
| BBR, m-value | -12 | 0.36 | 0.31 | 0.30 | 0.32 | Min. 0.3 |
| PG 76-22 | | Pass | Pass | Pass | Pass | |

72.3% higher than that of the control asphalt binder. Hence, the compaction of the WMA-B mixture can be harder than other WMA mixtures. It will be examined further in the compaction test of the mixtures. Besides, the penetration at 25°C of the control and WMA binders was close to 602. It means that the addition of the WMA additives did not alter the viscosity at 25°C,

i.e., the viscosity reduction effect of the WMA additives could vanish as the WMA binders cooled down to room temperature.

Besides, after RTFO short-term aging, the residual penetrations of the WMA-B and WMA-C binders were approximately 51% which was lower than that of the control asphalt binder and did not meet the minimum requirement of 55%. The residual penetration rates of the WMA-A and WMA-D binders were 71.9% and 67.7%, respectively. Thus, the WMA-B and WMA-C additives reduced short-term aging of the asphalt binder. Conversely, the WMA-A and WMA-D additives resulted in an increase of short-term aging.

#### 4.1.2 Effect of WMA additives on Performance Grade of Polymer Modified Asphalt Binder

The main purpose of this analysis was only to check whether or not the PMA with the WMA additives meet the PG requirements of the PMA. Thus, some laboratory tests were conducted in limited temperature conditions. For example, the DSR and BBR tests were conducted only at a specific temperature corresponding to PG 76-22: the DSR tests at 76°C for original binder and RTFO residue, 31°C for the PAV residue and the BBR tests at -12°C for the PAV residue. The PG test results of the PMA and WMA-PA, WMA-PB, and WMA-PC binders are summarized in Table 4.

The penetrations at 25°C of the WMA-PA and WMA-PB binders were 29 and 35, respectively, which were significantly lower than its requirements of 60 to 80. Hence, the addition of the WMA additives to the PMA increased the viscosity at intermediate pavement temperature significantly. On the other hand, the viscosity at 135°C of the WMA-PA and WMA-PB binders was reduced by 70 to 80% compared to that of the PMA. After RTFO aging, the residual penetration of the WMA-PA and WMA-PB binders met the minimum requirement of 55%. Hence, short-term aging did not stiffen the WMA-PA and WMA-PB significantly.

From the DSR test results at 76°C, the PMA with and without WMA additives met the high temperature PG requirements. The $G^*/\sin\delta$ values with the RTFO residue for the PMA and WMA-PA and WMA-PC binders were slightly over the minimum requirement of 2.2 kPa except the WMA-PB whose $G^*/\sin\delta$ value was 3.69 kPa. However, the $G^*/\sin\delta$ value with the original WMA-PB binder was slightly higher than the minimum requirement of 1.0 kPa. Considering all the test results, the high temperature of the PMA with and without WMA additives could pass their requirements. In addition the DSR and BBR tests with the PAV residue showed that the PMA met the low temperature PG requirements. Since the m-value of the PMA with and without WMA additives was slightly higher than its minimum requirement of 0.3, it is not possible to bump down low temperature PG. Therefore, the WMA additives did not alter the PG of the PMA.

### 4.2 Compactability of the WMA Mixtures

#### 4.2.1 Laboratory Test Results

The air voids of the WMA mixtures produced at various temperatures were measured for the laboratory- and field-mixed PG 64-16 mixtures and laboratory-mixed PG 76-22 mixtures. The variations of the air voids of the control and WMA mixtures with respect to compaction temperatures are shown in Fig. 2. As compaction temperature increased, corresponding air voids of the mixtures decreased. Most of the WMA mixtures could be compacted at 20 ~ 40°C lower than the control mixtures.

For the laboratory-mixed PG 64-16 mixtures, the compaction temperature of the control HMA mixture at the air voids of 4.0% was 143°C as shown in Fig. 2(a). In this study, the temperature reduction of the WMA mixtures was targeted as 30°C or more.

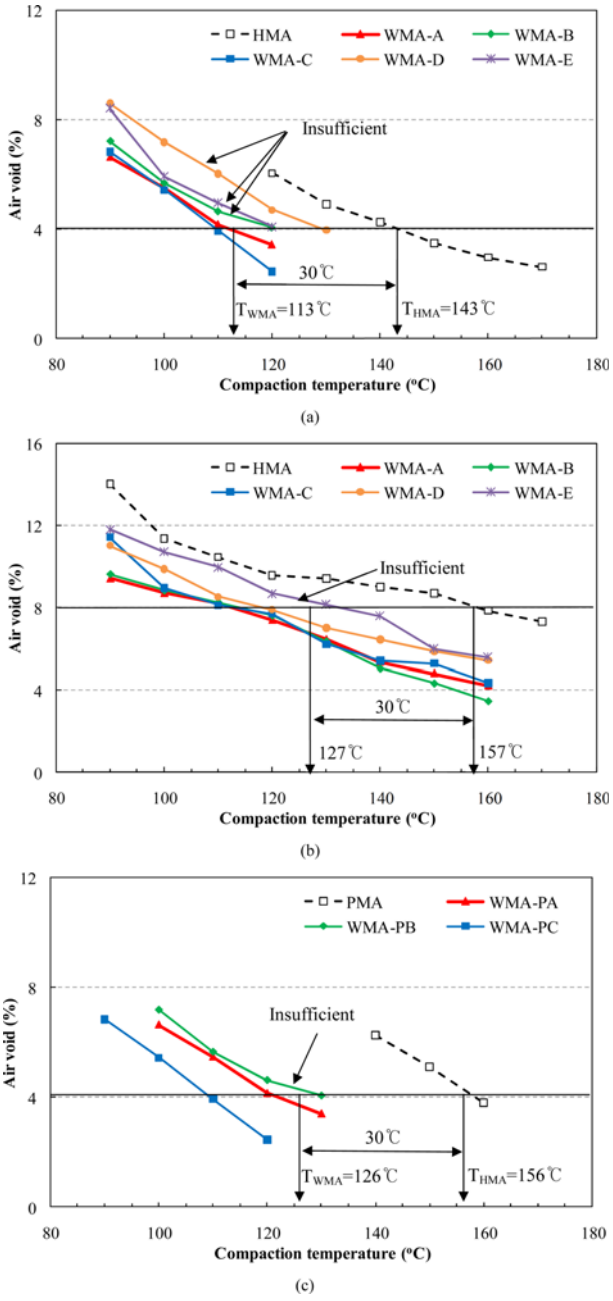


Fig. 2. Air Void at Various Compaction Temperatures: (a) Laboratory-mixed PG 64-16 Mixtures, (b) Field-mixed PG 64-16 Mixtures, (c) Laboratory-mixed PG 76-22 Mixtures

Thus, the maximum compaction temperature of the WMA mixtures was determined to be 113°C. The temperature reduction was 10°C by the WMA-D, 23 ~ 24°C by the WMA-B and -E, and 31 ~ 33°C by the WMA-A and -C. Thus, the WMA-A and WMA-C additives had the most efficient on reducing compaction temperature.

For the field-mixed PG 64-16 mixtures, the compaction temperature of the control HMA mixture at the air voids of 8.0% was 157°C as shown in Fig. 2(b). At the target compaction temperature of 127°C, all the field-mixed WMA mixtures could be compacted properly except the WMA-E mixture. The temperature reduction of the WMA-A, -B, and -C mixtures was approximately 44°C and that of the WMA-D and WMA-E mixtures was 37°C and 21°C, respectively. Thus the field-mixed WMA mixtures had better temperature reduction effects, 13.6°C more in average, than the laboratory-mixed WMA mixtures. Besides, it was found from Fig. 2(a) and 2(b) that the slope of the air void versus compaction temperature curve was different in the HMA and WMA mixtures. The slope of the HMA mixtures was approximately 0.058%p/°C regardless of the mixing methods. The slope of the laboratory- and field-mixed WMA mixtures was 0.124%p/°C and 0.087%p/°C, respectively. It means that the compactability of the WMA mixtures is more sensitive to temperature than that of the HMA mixtures. Also, the laboratory-mixed WMA mixtures showed 30% higher temperature sensitivity than the field-mixed WMA mixtures. Therefore, it is critical to control the compaction temperature of the WMA mixtures because of significantly higher temperature sensitivity on the compaction of the WMA mixtures.

The compaction temperatures of the PG 76-22 control and WMA mixtures were 156°C and 126°C, respectively as shown in Fig. 2(c). The use of polymer modified asphalt binder raised the compaction temperature by 16°C. The temperature reduction of the WMA-PA, WMA-PB, and WMA-PC mixtures was 35°C, 26°C, and 46°C, respectively. It reminds that since the temperature reduction of the WMA-A, WMA-B and WMA-C mixtures was 31°C, 24°C, and 33°C, respectively. Thus it can be concluded that the effects of these WMA additives are comparable in reducing the compaction temperature of the PG 64-16 and PG 76-22 mixtures.

Considering all the laboratory test results, the performance of the WMA additives on the compaction of the WMA mixtures can be concluded as follow. Regardless of the mixing method, the WMA-A and -C additives were successful in reducing compaction temperature more than 30°C; the WMA-E additives had the least function to lower compaction temperature. The WMA-B and WMA-D mixtures could not be compacted sufficiently at the target compaction temperature when they were prepared in laboratory, but they could be compacted properly when the field-mixed WMA mixtures was used.

### 4.2.2 Field Test Results

The test sections with the PG 64-16 HMA and WMA mixtures were constructed properly. The HMA mixture was produced at 176°C which is slightly higher than its target temperature of 170°C and compacted at the target temperature of 140°C. The target mixing temperature was 140 ± 5°C and compaction temperature was 110 ± 5°C. The WMA mixtures were produced properly at a range of 135 ~ 143°C and compacted suitably at 106 ~ 109°C. Among them, the WMA-D mixtures were produced at 5°C lower temperature; the WMA-B mixtures were produced at 3°C higher temperature. The laboratory and field compaction test results are summarized in Table 5.

Using core samples from the pavement sections, the $G_{mb}$ of the pavements were measured to compute the degree of compaction. The HMA section met the target degree of compaction of 96%. However, the degree of compaction of the WMA sections ranged 94.1 to 95.7% which did not meet the target degree of compaction. Of the WMA mixtures, the compaction of the WMA-A and WMA-C sections could be marginal in that the degree of compaction was approximately close to 96%. However, the degree of compaction of the WMA-D and WMA-E sections was insufficient, more than 1%. The lack of compaction in the WMA sections might result from strong winds at the site and higher temperature sensitivity of the WMA mixtures. Thus, it is recommended to increase the mixing and compaction temperature of the WMA mixtures by 10°C or higher for proper construction at cold and/or windy weather.

The ranking of the degree of compaction of the WMA pavements is compared with other rankings based on the laboratory tests. The WMA-A and WMA-C mixtures with lower viscosity at 135°C and efficient compaction temperature reduction were

Table 5. Summary of the Compactability of the PG 64-16 WMA Mixtures

| Mix Type | Viscosity at 135°C (Pa·s) | Laboratory | | Field | | |
|---|---|---|---|---|---|---|
| | | Compaction Temperature (°C) | | Temperature (°C) | | Degree of Compaction (%) |
| | | 4% Air Voids (Lab. Mixes) | 8% Air Voids (Field Mixes) | Mixing | Compaction | |
| HMA | 0.415 | 143 | 157 | 176 | 140 | 97.8 |
| WMA-A | 0.385 (2) | 112 (2) | 113 (1) | 137 | 106 | 95.7 (1) |
| WMA-B | 0.715 (5) | 119 (3) | 114 (3) | 143 | 109 | 95.2 (3) |
| WMA-C | 0.345 (1) | 110 (1) | 113 (1) | 140 | 109 | 95.7 (1) |
| WMA-D | 0.435 (4) | 133 (5) | 120 (4) | 135 | 106 | 94.7 (5) |
| WMA-E | 0.400 (3) | 120 (4) | 136 (5) | 139 | 106 | 94.1 (4) |

*Number in the parenthesis means ranking among the WMA mixes.

compacted in the field better than other WMA mixtures. The compactability of the WMA-B mixture was ranked third in the field and laboratory despite of the highest viscosity at 135°C. The WMA-D and WMA-E mixtures had the worse insufficient compactability, which is the same result regarding temperature reduction. From these comparisons, the viscosity at 135°C could not be a proper indicator related to the degree of compaction in field. Instead, the compactability of the WMA mixtures can be estimated with the temperature reduction effect in laboratory tests.

### 4.3 Performance of the WMA Mixtures

The performance of the WMA was evaluated using the wheel tracking test for rutting resistance and the IDT strength test for crack resistance and moisture susceptibility. In the performance tests, the field-mixed samples obtained from the field test sections were used for the PG 64-16 mixtures. Because of lack of field-mixed samples, laboratory-mixed PG 76-22 mixtures were used. Note that because of different sample preparations, it will not be able to compare the performance test results directly.

#### 4.3.1 Rutting Resistance

The variations of rut depth with respect to the number of load cycles obtained in the wheel tracking test are shown in Fig. 3. As shown in Fig. 3(a), the PG 64-16 WMA mixtures had lower rut depth than the HMA mixture, except for the WMA-D mixture. With the consideration of the high temperature PG of the WMA, it is reasonable that that WMA-A and WMA-B having higher high temperature PG of 70-XX resulted in lower rut depth than the HMA of the PG of 64-16 as expected. However, WMA-C and WMA-E of a PG of 64-XX also had lower rut depth than the HMA. Thus, it might be concluded that the high temperature PG of the WMA cannot represent rutting resistance well.

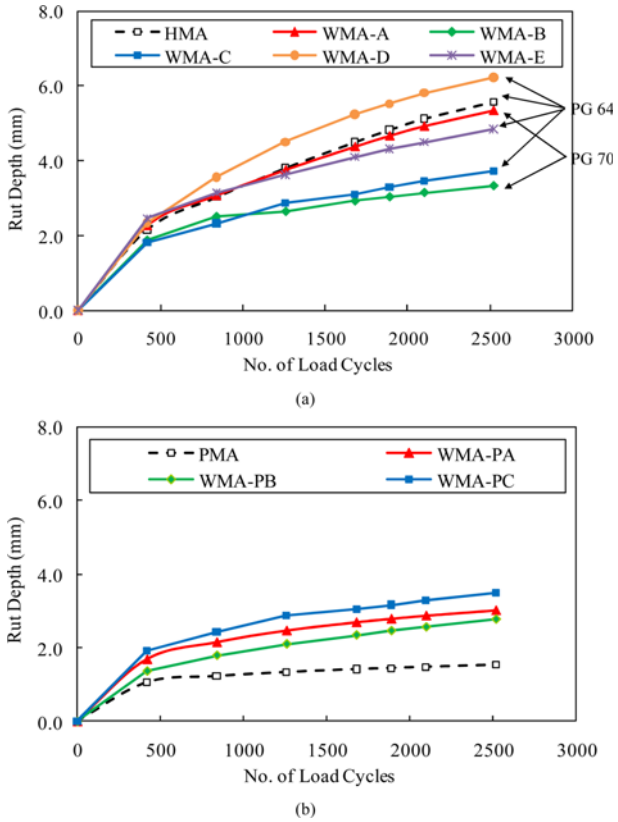


Fig. 3. Rut Depth Variations with Respect To Number of Load Cycles: (a) Field-mixed HMA and WMA Mixtures, (b) Lab-mixed PMA and WMA Mixtures

As shown in Fig. 3(b), rut depth of the PMA mixture was almost half of that of the WMA mixtures. The addition of the polymer modifiers to the straight asphalt binder in the HMA mixtures resulted in significant reduction in rut depth at 2,520 load cycles of almost 70%. The rut depth of the WMA-PA mixtures was reduced by 40% compared to the WMA-A mixtures. However, this rut depth reduction effect was not significant for the WMA-PB and WMA-PC mixtures. Overall, the addition of the WMA additives to the PG 64-16 asphalt binder enhanced rutting resistance up to 40% for WMA-B. For the PG 76-22 PMA mixtures, however, it resulted in a negative effect on rutting resistance. Hence, the performance of the WMA mixtures in terms of rutting resistance depends on the type of WMA additives as well as the PG of asphalt binder.

#### 4.3.2 Moisture Susceptibility

Moisture susceptibility of the WMA mixtures was evaluated based on the Tensile Strength Ratio (TSR) which is the ratio of tensile strength obtained in a dry condition to a wet condition. The IDT strength test results with the TSR of the HMA and WMA mixtures are listed in Table 6. Except the WMA-C, WMA-E, and WMA-PC, the TSR of most mixtures was greater than its requirement of 0.8 in which freeze-thaw procedure is not included in Korea. Thus, most of the WMA mixtures were not vulnerable to moisture damage. The average of the PG 64-16 WMA mixtures and the PG 76-22 WMA mixtures was 0.82 and 0.79. Thus the PG of the asphalt binder did not affect the TSR of the WMA mixtures significantly. However, the TSR of the WMA-C, WMA-PC, and WMA-E was found to be 0.72, 0.64, and 0.78, respectively. Furthermore, IDT wet strength of the three WMA mixtures was also smaller than that of other WMA

Table 6. Tensile Strength and Tensile Strength Ratio (TSR) of the HMA and WMA Mixtures

| Mixtures | | IDT Strength (MPa) | | TSR | |
|---|---|---|---|---|---|
| | | Dry condition | Wet condition | | |
| HMA | | 0.729 | 0.634 | 0.87 | |
| WMA | A | 0.906 | 0.795 | 0.88 | 0.82 |
| | B | 0.859 | 0.743 | 0.87 | |
| | C | 0.802 | 0.581 | 0.72 | |
| | D | 0.826 | 0.689 | 0.83 | |
| | E | 0.776 | 0.605 | 0.78 | |
| PMA | | 0.932 | 0.862 | 0.93 | |
| WMA | PA | 0.859 | 0.763 | 0.89 | 0.79 |
| | PB | 0.907 | 0.774 | 0.85 | |
| | PC | 0.780 | 0.497 | 0.64 | |

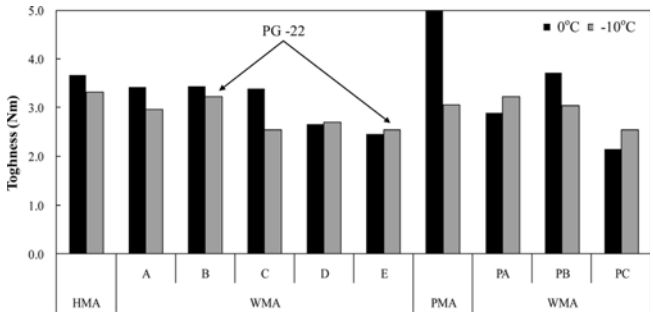


Fig. 4. Comparison of the Toughness of the WMA Mixtures

mixtures. Thus, when the WMA additive C is used for the PG 64-16 and PG 76-22 mixtures, it is required to use anti-stripping agents to enhance moisture resistance of the WMA.

### 4.3.3 Crack Resistance

Crack resistance of the WMA mixtures was evaluated based on toughness obtained from the IDT strength tests. Toughness represents a mechanical deformation energy prior to fracture and can be calculated by measuring area under a displacement-load curve until the maximum load is achieved. Fig. 4 shows the toughness of the mixtures at 0°C and -10°C. The toughness at 0°C of the WMA-D and WMA-E mixtures was approximately 30% worse than other PG 64-16 mixtures. Similar trend was observed at -10°C except that the toughness of WMA-C decreased considerably and was comparable to that of the WMA-D and -E. Considering the low temperature PG, it is not reasonable because the WMA additive E enhanced the low temperature PG from -16 to -22. Among the PG 76-22 mixtures, the toughness of WMA-PC was the lowest at 0°C and -10°C. In average, the PG 64-16 WMA mixtures had 16.2% at 0°C and 16.1% at -10°C lower toughness than the HMA mixture; the PG 76-22 WMA mixtures had 41.8% at 0°C and 4.6% at -10°C lower than the PMA mixture. So, the WMA mixture would be more critical against cracking.

## 5. Conclusions

In this study, various laboratory and field tests were conducted to evaluate the effect of WMA additives on the performance grade of straight and polymer modified asphalt binder and the performance of asphalt mixtures. It was found that WMA additives influenced the performance grade in low and/or high temperature for the straight asphalt binder of PG 64-16, but did not alter the performance grade for the polymer modified asphalt binder of PG 76-22. However, the effect of the WMA additives on the viscosity at 135°C related to mixing and compaction was not significant for the straight asphalt binder, but significant for the polymer modified asphalt binder. The WMA-A and WMA-D additives were less sensitive on aging or stiffening of asphalt binder.

The compactability of the WMA mixtures was evaluated in the laboratory. From the laboratory compaction tests, it was found that the effect of the WMA additives on reducing compaction temperature was approximately 30°C regardless of the types of PG of asphalt binder. The compaction temperature reduction of the WMA-A and WMA-C additives was slightly higher than 30°C and that of the WMA-B and WMA-E additives was lower than 30°C. It was also found that a mixing procedure could have an effect on the compaction temperature of the WMA mixtures. The WMA-D mixture manufactured with plant loose mixtures was sufficiently compacted at lower temperature than the WMA-D mixture prepared in the laboratory.

Furthermore, the compactability of WMA mixtures was evaluated in field. The HMA section met the target degree of compaction but the degree of compaction in the WMA sections was 94.1 to 95.7%, slightly lower than the minimum requirement of 96%. In the WMAs pavements, it was inadequate to lower mixing and compaction temperature by 30°C. The WMA-A and WMA-C pavements showed relatively better degree of compaction of 95.7% than other WMA pavements. It was the same result as the laboratory tests that the WMA-A and WMA-C additives had higher compaction temperature reduction than other WMA additives. Thus, it can be concluded that the ranking of the degree of compaction in field was closely related to the compaction temperature reduction, but not to viscosity at 135°C or PG of asphalt binder.

To evaluate the performance of the WMA mixtures, the rutting and crack resistance tests were carried out. From the field test using the field-mixed mixtures, the rutting resistances of WMA was higher than HMA except for WMA-D. However, the rutting resistance of WMA was lower than PMA when the lab-mixed mixtures were utilized. In the crack resistance test, the PMA indicated the highest level of toughness in IDT test at 0°C.

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