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Effect of Weathering on Rubberized Porous European Mixture

Zhaoxing Xie¹ and Junan Shen, Ph.D., M.ASCE²

Abstract: This project investigated the effect of weathering (UV light, oxidative, and water) on the performance of rubberized porous European mix (PEM) by laboratory tests and field pavement investigation. Three rubberized PEM mixes were produced by three processes: the dry process, the wet process, and the terminal blend in the laboratory. For comparison purposes, PEM mixture containing styrene-butadiene-styrene (SBS)-modified binder was also used. Weathering for 1,000 and 3,000 h on compacted PEM mixes were conducted. Dynamic modulus, rutting/moisture resistance, and Cantabro loss were measured for each mixture and aging condition. Additionally, the test sections of rubberized and SBS-modified PEM in Georgia were investigated through a visual inspection on the pavements and laboratory testing on core samples. The results indicated that (1) the weathering had increased the elastic properties and the rutting resistance, but had no significant effect on the moisture resistance and decreased the raveling resistance of PEM mixes; (2) the effect of weathering was more on the performance properties of rubberized PEM mixes in the dry process and the wet process than those of the SBS control PEM; (3) the first 1,000-h weathering had more effect on the dynamic modulus and the Cantabro loss of PEM mixes than the last 2,000-h weathering; and (4) all PEM field test sections of the dry process, the wet process, and the control showed excellent performance after 3 or 5 years of service. DOI: 10.1061/(ASCE)MT.1943-5533.0001551. © 2016 American Society of Civil Engineers.

Author keywords: Porous European mix; Crumb rubber; Weathering; Performance.

Introduction

Crumb rubber modifier (CRM), made from scrap tires, has been introduced into the production of hot mix asphalt (HMA) because it improves resistance to rutting (Cooper et al. 2007; Xiao et al. 2007). The processes of incorporating CRM in HMA can be divided into three categories: a dry process, a wet process, and the terminal blend. In the wet process, the crumb rubber and binder are completely mixed to form rubberized binder, which is then mixed with aggregates in a drum at a mix plant. In the dry process, the crumb rubber is mixed directly with aggregates in the drum to produce an HMA. The terminal blend binder is produced by mixing CRM and polymers [i.e., styrene-butadiene-styrene (SBS)] at a supplier's terminal and shipped to the asphalt mix plant and stored in the plant's binder storage tanks.

Many studies have evaluated the properties of the rubberized HMA in the wet process. Some states, like Arizona, California, Florida, and Louisiana, have well-established specifications or recommendations on the design and production of asphalt rubber (AR) HMA based on both laboratory and field tests (Hicks et al. 1995; Huang et al. 2002). Kaloush et al. (2003) found the wet process mixture had higher modulus values than the performance grade (PG) 64-22 conventional mixture at high temperatures; and lower modulus values at low temperatures. Willis et al. (2014) reported that wet process HMA used in Alabama was typically stiffer than the polymer-modified mixture in terms of dynamic modulus testing.

Studies about rubberized HMA in the dry process were limited. Rahman et al. (2010) found rubberized mixes in the dry process to be more susceptible to moisture with the degree of susceptibility primarily depending on the amount of rubber in the mixture. Pasetto and Baldo (2008) reported that the dry process HMA had a longer fatigue life, better stiffness behavior at lower temperatures, and greater permanent deformation resistance at high temperatures than conventional mixes. However, relatively little is known about the aging characteristics of rubberized HMA. Reed (2010) investigated the effects of aging on the wet process mixes and found that the effects of aging on the wet process mixes are highly dependent on temperature.

In addition, current methods of aging asphalt binder and HMA, i.e., rolling thin film oven test (RTFOT), pressure aging vessel (PAV), and long-term oven aging, primarily focus on thermal aging. However, field asphalt pavement was weathered under the combined environment of light, water, and thermal cycling, so current aging methods are not sufficient to simulate field-aging behavior (Houston et al. 2005). The development of an advanced aging test method considering all the aforementioned factors will provide a useful tool for the assessment of the asphalt mixture aging. Hagos (2008) reported the effect of combined environment factors (UV light, oxidative, and moisture) on the performance of HMA, suggesting that combining the effects of temperature, UV light, and moisture during aging may be a practical aging protocol to simulate field aging conditions. Grzybowski et al. (2012) developed the accelerated pavement weathering system (APWS) to simulate the combined environment of UV light, oxidative, and water and performed the effect of weathering on the HMA performance.

Porous European mix (PEM) with CRM is commonly used in Georgia. It is well known that PEM is vulnerable to weathering and moisture damage because PEM has a high amount of air voids and is directly weathered under the combined environment of light,
water, and thermal cycling. Therefore, it is necessary to determine the effect of the weathering on the rubberized PEM performance.

**Objectives and Scope**

The objective is to explore the effect of a combined environment (UV light, oxidative, and water) on the performance of rubberized PEM mixes by laboratory tests and field pavement investigation. In addition, for comparison purposes, the PEM mixture containing SBS-modified binder was also investigated. To achieve the objective, three rubberized PEM mixes were produced by three processes: the dry process, the wet process, and the terminal blend in the laboratory. Optimum asphalt contents (OAC) of the aforementioned four PEM mixes were designed according to the specification of the Georgia Department of Transportation (2013). Two weathering levels (1,000- and 3,000-h weathering) were selected. The effect of weathering on the performance of the PEM mixes was evaluated in terms of dynamic modulus, rutting/moisture resistance, and Cantabro loss. Dynamic modulus testing was performed using the asphalt mixture performance tester (AMPT) system. Rutting resistance and moisture susceptibility were analyzed by the Hamburg wheel tracking test. Cantabro loss was measured by the Cantabro test. Additionally, the test sections of rubberized and SBS-modified PEM in Georgia were investigated through a visual inspection of the pavements and laboratory testing on core samples. Fig. 1 shows the flow chart for this study. No terminal blend PEM test sections were paved, and only laboratory test results were analyzed on terminal blend PEM in this study.

**Experiment: Materials and Sample Preparation**

Four PEM mixtures were produced using four asphalt binders: rubberized binder in the dry process (dry process PEM), rubberized binder in the wet process (wet process PEM), the terminal blend binder modified by both CRM and SBS (hybrid PEM), and SBS-modified binder (SBS PEM). Based on the CRM engineering application in Georgia, the wet process rubberized binder was produced by mixing 10% - 30 mesh ambient CRM with a virgin binder of PG 67-22 at 170°C and 700 RPM for 45 min in the laboratory. The dry process binder used the same CRM and virgin binder, which were introduced into aggregates together with a cross-link agent, transpolyoctenamer (TOR) polymer at 4.5% of the weight of the CRM.

To avoid excessive drain-down, mineral fiber at 0.4% by the weight of the total mixture was added to PEM mixtures. For anti-stripping purposes, hydrated lime at 1.0% by the weight of the total aggregate was used in all PEM mixtures. Gradations of 12.5-mm PEM shown in Table 1 were designed in accordance with Georgia mix design procedure, and optimum asphalt contents (OAC) of PEM were designed according to the specification of PEM design. Table 2 presents the OAC of PEM mixtures.

Mixture specimens were prepared in the following ways. The loose mixtures were aged in a forced-draft oven for 2 h ± 5 min at a compacted temperature before compaction to simulate the short-aging during the mixing and construction, and then the aged loose mixtures were compacted by a Superpave gyratory compactor (SGC). The SGC compacted samples were then cored/cut to the specified sizes for the dynamic modulus test and Hamburg wheel tracking test. Before proceeding to testing, air voids of all SGC samples are measured using the Corelok method, following AASHTO T331 (AASHTO 2015). All PEM specimens used in the study met the target air voids of 17.0 ± 1%. The dimensions and the air voids of PEM specimens are presented in Table 3.

**Test Method**

**Weathering Process**

Based on the previous study (Grzybowski et al. 2012) and the standard specifications, the weathering device was developed to simulate the combined environmental conditions of UV light, water, and temperature. The weathering device allows compacted asphalt mixture specimens to be weathered from the top surface down,

**Table 1. Aggregate Gradation of PEM Mix**

| Sieve [mm (in.)] | Percentage passing (%) |
|------------------|------------------------|
| 19.0 (3/4)       | 100                    |
| 12.5 (1/2)       | 82.7                   |
| 9.5 (3/8)        | 57.4                   |
| 4.75 (Number 4)  | 11.0                   |
| 2.36 (Number 8)  | 7.1                    |
| 0.075 (Number 200)| 2.1                    |

**Table 2. Optimum Asphalt Content of PEM Mix**

| Mix type | OAC (%) |
|----------|---------|
| Dry process | 6.0 |
| Wet process  | 6.5 |
| Hybrid       | 6.0 |
| SBS          | 6.0 |
simulating the natural aging of field asphalt pavement. The weathering device consists of a combined environmental chamber, water treatment system, and system controller (Fig. 2). The fluorescent UV-B lamps (Zoo Med Laboratories, San Luis Obispo, California) are used as detailed in 6.1.3.3 of ASTM G154 (ASTM 2012). Three UV-B lamps (Zoo Med Laboratories, San Luis Obispo, California) provide programmable lighting intensities. Fresh water is distilled by the distiller and cooled by the chiller to 7.2 ± 3°C according to ASTM standard D4799 (ASTM 2008). A heater inside the environmental chamber ensures the temperature of the environmental chamber remains at 60°C. Testing parameters for one weathering cycle are as follows: first a 51-min UV light exposure, and then a 9-min UV light and water spray. The weathering temperature was 60°C. The parameters for the weathering device come from the cycle requirements outlined in ASTM Standards D4799 and D4798 (ASTM 2011). Two long-term weathering levels (1,000- and 3,000-h weathering) were selected in this study. It was reported that the 3,000-h weathering is similar to PAV aging (Grzybowski et al. 2012).

### Dynamic Modulus Test

PEM mixture is the typical linear viscoelastic (LVE) material, which exhibits time- and temperature-dependent behavior. In the study, dynamic modulus tests ($E'$) were conducted to measure the LVE behavior of PEM mixtures. Dynamic modulus tests were performed in load-controlled and axial compression mode using AMPT. In this test, the strain amplitudes were controlled below 115 microstrains to ensure the specimen response was within a linear viscoelastic limit. Three replicate specimens at a target air void level were tested at three temperatures (4, 20, and 45°C) and four loading frequencies (0.01, 0.1, 1, and 10 Hz) according to the AASHTO TP79-12 (AASHTO 2012) requirement. Prior to $E'$ testing, the specimens were conditioned in an environmental chamber to reach the test temperature stipulated in AASHTO 13 TP79-12. Conditioning times for the $E'$ test at 4, 20, and 45°C were 18, 3, and 3 h, respectively.

### Cantabro Test

The raveling resistance of PEM mixture is generally investigated using the Cantabro loss. The Cantabro loss test can evaluate the bonding properties between the aggregate particles and asphalt binders by abrasion and impact effect. In this test, the gyration samples with a diameter of 150 mm and a height of 130 mm are weighed and placed in a Los Angeles abrasion tester (Humboldt Manufacturing Company, Elgin, Illinois) without the use of the steel ball, and the drum was turned for 300 revolutions. The percentage of mass loss during this process is used to evaluate the raveling resistance of the PEM mixture. Cantabro loss was calculated using Eq. (1). For each mix, three replicates were tested in the study

$$ CL = \left( \frac{A - B}{A} \right) \times 100 $$

where $CL$ = Cantabro loss (%); $A$ = initial weight of test specimen; and $B$ = final weight of test specimen.

### Laboratory Testing Results

#### Influence of Weathering on Viscoelastic Property

The dynamic modulus of a material is a viscoelastic test response developed under sinusoidal loading conditions. Dynamic modulus can characterize the strength and load resistance of PEM mixes. Fig. 3 shows the $|E'|$ master curve of unweathered and weathered PEM samples. The $|E'|$ values of PEM mixtures increased with the increase of the weathering time, suggesting the weathering resulted in the increase of the strength and load resistance of PEM. To determine whether $|E'|$ values of the four PEMs were significantly different at the same weathering level, a t-test ($\alpha = 0.05$) was conducted and the results showed no significant difference in $|E'|$ values, regardless of unweathering or weathering. To compare $|E'|$ for

### Table 3. Sample Dimensions and Air Voids

| Test type                      | Diameter × height (mm × mm) | Target air void (%) | Dry process | Wet process | Hybrid | SBS |
|-------------------------------|----------------------------|---------------------|-------------|-------------|--------|-----|
| Dynamic modulus test          | 100 × 150                  | 17.0 ± 1            | 16.8        | 17.2        | 17.0   | 17.2|
| Cantabro test                 | 150 × 130                  | 17.0 ± 1            | 17.0        | 16.6        | 17.3   | 17.0|
| Hamburg wheel tracking test   | 150 × 62                   | 17.0 ± 1            | 16.7        | 17.1        | 16.7   | 17.4|

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Each PEM between weathering levels—unaged versus 1,000-h aging and unaged versus 3,000-h aging—another t-test ($\alpha = 0.05$) was performed; and the results showed no difference between $|E'|$ of unaged and 1,000-h aging, whereas statistical differences in $|E'|$ were found between unaged and 3,000-h aging at low frequency and low temperatures (0.1 Hz at 4 and 20°C) or high temperature (45°C), indicating that 3,000-h weathering had a significant effect on the $|E'|$ of each PEM mixture and that it depended on temperature and loading frequency, i.e., weathering had more effect on $|E'|$ at a low frequency or a high temperature than a high frequency or a low temperature.

Black space curves are generally used to investigate the effect of aging on the viscoelastic properties of asphalt mixes or binders. Black space curves exhibit the relationship between the phase angle and the dynamic modulus of asphalt mix or binders. The phase angle is a direct indicator of the viscoelastic properties of the asphalt mix. The value of phase angle equal to zero indicates that the material is behaving as a pure elastic material. A value of phase angle equal to 90 indicates a pure viscous (Newtonian) material. Fig. 4 shows the black space curves of the four PEM. Fig. 4 shows that the black space curves moved to the left on the $x$-axis as PEM was weathered, and the phase angles of the four PEM mixes decreased with the weathering time for a given value of dynamic modulus. This suggests that the weathered PEM exhibited more elastic behavior than the unweathered. Additionally, the moving distances to the left caused by the first 1,000-h weathering were more than those by the last 2,000-h weathering, indicating the weathering rate decreased with the increase of weathering time. Furthermore, for a given value of dynamic modulus, the PEM in the dry process and wet process seem to have the lower phase angle values, especially at low frequencies (or high temperatures). This shows that the PEM in the dry process and wet process exhibit...
lower elasticity compared with hybrid and SBS PEM at higher temperatures.

Influence of Weathering on Rutting/Moisture Resistance

Fig. 5 presents the results from the Hamburg wheel-tracking test for unweathered and 3,000-h weathered PEMs. Fig. 6 shows the rutting after 20,000 wheel passes and the rutting ratio that was calculated through Eq. (2). The unweathered dry process PEM exhibited the highest rutting (12.1 mm), followed by the unweathered wet process (10.2 mm); and the unweathered hybrid and SBS PEMs showed much lower rutting (5.6 and 5.5 mm, respectively). After the 3,000-h weathering, the dry process and the wet process PEMs still exhibited higher rutting than the hybrid and SBS PEMs. However, the differences of the rutting between them significantly decreased. Fig. 6 indicated that the PEMs containing CRM showed the higher rutting ratio than the SBS PEM, suggesting the weathering could have more effect on the rutting resistance of the rubberized PEM mixes than that of the SBS PEM. This phenomenon may be attributed to the inaction of CRM with asphalt binder during the weathering. It was also found that no PEM exhibits a stripping inflection point, regardless of being unweathered or weathered, which indicated that no PEM mixes showed significant moisture damage after 20,000 wheel passes, and the weathering could have no significant effect on the moisture resistance of the four PEM mixes.

\[
\text{Rutting Ratio} = \frac{\text{Rutting}_{\text{weathered}}}{\text{Rutting}_{\text{unweathered}}} \tag{2}
\]

where Rutting_{unweathered} = rutting value of unweathered PEM; and Rutting_{weathered} = rutting value of 3,000-h weathered PEM.

Influence of Weathering on Raveling Resistance

Cantabro loss is an index to evaluate the raveling resistance of PEM. Fig. 7 shows the Cantabro loss results for unweathered and weathered PEMs. For the unweathered condition, hybrid PEM showed slightly higher Cantabro loss (18.4%); the dry process and wet process PEMs had similar Cantabro losses (17.7% and 17.4%, respectively); SBS PEM had the least Cantabro loss at 14.9%. After the 1,000-h weathering, Cantabro loss for the four PEM mixes increased. The increase of Cantabro loss was significantly higher for the dry process and wet process PEMs compared to the hybrid and SBS PEMs. This means more loss of bond between aggregate and binder could occur in the dry process and wet process PEMs. Additionally, the increase rate of Cantabro loss of PEMs significantly decreased after the 1,000-h weathering, suggesting the effect of the weathering on the Cantabro loss of PEMs significantly decreased after 1,000 h. Furthermore, SBS PEM always had the least Cantabro loss among the four PEMs, regardless of unweathering or weathering.

Field Performance

To evaluate the field performance of the rubberized asphalt mix, test sections of rubberized and control SBS-modified PEM were paved on SR 247 at Macon (2011), I-75 at Valdosta (2009), and I-75 at Perry (2007) in Georgia. The rubberized PEM used in these three sections consisted of 30 mesh crumb rubber at 10% of the weight of the asphalt cement, TOR polymer at 4.5% of the weight of the crumb rubber (only for the dry process), an asphalt binder of PG 67-22, and crushed granite aggregate. The optimum asphalt binder content (OAC) of both rubberized and control PEM mixes is 6.0% (Hines 2007). Rubberized and control PEM test sections were evaluated by field visual inspection after 3 years of service for SR 247 Macon and I-75 Valdosta, and 5 years of service for I-75 Perry. Additionally, field core samples were investigated by Hamburg wheel track tests. Table 4 presents the thickness, locations, annual average daily traffic (AADT) and average annual daily truck traffic (AADTT) about three test sections by the date of investigation. AADT and AADTT of each test section was calculated based on the traffic data of Georgia DOT.
Field Visual Inspection Results

Table 5 summarizes the visual inspection results of three test sections as measured by rut depth, cracking, raveling, bleeding, pushing, and potholes. After 3 years of service, the field performance of the rubberized PEM pavement is similar to that of the control PEM pavement. Cracking, raveling, bleeding, pushing, and potholes were not found on the dry process, the wet process, and control SBS PEM pavement in SR 247 Macon and I-75 Valdosta. The dry process and control PEM pavements in I-75 Perry performed similarly after 5 years in service, except for 7 m of raveling at the beginning of the dry process PEM test section. In addition, reflective cracking was observed in both the dry process and control PEM test sections in I-75 Perry, and their interval, length, and severity were similar. PEM pavement in SR 247 Macon and I-75 Perry showed minor rutting [3 or 4 mm (2.0/16 or 2.5/16 in.)]. Overall, the dry process, the wet process, and the control PEM pavement exhibited excellent performance after 3 or 5 years of service.

Rutting/Moisture Resistance of Field Core Samples

Field PEM samples with 150-mm diameter were cored from the dry process, wet process, and control SBS PEM pavement on SR 247 Macon. The Hamburg wheel tracking tests on the core samples were performed to evaluate the resistance to rutting and moisture susceptibility of field pavement using APA. To meet the thickness requirement of 62 mm of Hamburg wheel-tracking test, each specimen consisted of two layers of HMA: a 25 mm (1-in.) surface layer of PEM on a 38 mm (1.5-in.) rubberized Superpave in the dry process (Fig. 8). The PEM types of surface layer included the dry process PEM, the wet process PEM, and the control PEM. The rubberized Superpave mixture in all specimens was the same. Four core samples for each PEM test section were measured: two

| Location      | Pavement type | Cracking | Raveling (%) | Bleeding, pushing, and pothole | Average rut (mm (1/16 in.)) |
|---------------|---------------|----------|--------------|-------------------------------|-----------------------------|
| I-75 Valdosta | Dry process   | None     | None         | None                          | 0 (0)                       |
|               | Control       | None     | None         | None                          | 0 (0)                       |
| I-75 Perry    | Dry process   | Reflective cracking, average interval: 9 m | 0.4           | None                          | 3 (2.0)                     |
|               | Control       | Reflective cracking, average interval: 9 m | None          | None                          | 3 (2.0)                     |
| SR 247 Macon  | Dry process   | None     | None         | None                          | 4 (2.5)                     |
|               | Wet process   | None     | None         | None                          | 4 (2.5)                     |
|               | Control       | None     | None         | None                          | 3 (2.0)                     |

Fig. 8. Core specimen location and APA test sample

Fig. 9. Hamburg wheel tracking on field core samples
samples were from the wheel path, and another two were from the center path (Fig. 8).

Fig. 9 shows the average deformation on the four core specimens for the dry process, wet process, and control PEM pavement. Average rut depth of the dry process PEM mix was slightly lower than that of the wet process, while significantly higher than that of the control PEM mix after 20,000 wheel passes. Although the dry process and the wet process PEM exhibited higher rut depth than control PEM, no significant difference of rutting in field PEM pavement was found.

Fig. 9 also shows that no PEM exhibits a stripping inflection point, suggesting that no core sample shows significant moisture damage after 20,000 wheel passes. In addition, a rutting depth of 12.5 mm after 20,000 passes indicates less susceptibility to moisture damage (Brandon et al. 2014). The dry process, wet process, and control mixes pass the criteria.

Cantabro Loss of Field Core Samples

Field PEM samples with 100-mm diameter and 25.4-mm thickness were cored from the dry process and control PEM pavement on I-75 at Valdosta, and I-75 at Perry, and then Cantabro tests were performed on these core samples. A standard number of Cantabro revolutions is 300 for the standard Marshall sample with a 63.5-mm thickness. However, the core samples taken from the test sections, like a hockey puck, were much thinner than the standard Marshall sample. It is not possible to use the standard revolution of 300 for the aged hockey puck samples because they could break at fewer revolutions. In the study, the trials of the Cantabro test were conducted on the core samples to determine the suitable number of revolutions that is defined at which the sample starts to break. Based on the trial test results, 40 and 10 cycles were selected for the core samples taken from I-75 Valdosta and I-75 Perry, respectively. The air voids of the PEM core samples of both I-75 Valdosta and I-75 Perry were shown in Table 6. Fig. 10 shows that the Cantabro loss results of PEM core samples. The dry process PEM had higher values of the Cantabro loss than the controls, regardless of whether its air voids were higher or lower than the control.

Summary and Conclusions

This paper investigated the effect of weathering on the performance of rubberized PEM mixes and compared their performance characteristics with SBS PEM mixes. The evaluated performance properties included the dynamic modulus, rutting resistance, moisture susceptibility, and Cantabro loss. The following conclusions may be offered based on the testing results:

- The 1,000- and 3,000-h weathering (UV light, oxidative, and water) increased the elastic properties and the rutting resistance, while decreased the raveling resistance of PEM mixes;
- The first 1,000-h weathering had more effect on the dynamic modulus and Cantabro loss than the last 2,000-h weathering;
- No PEM mixes showed significant moisture damage after 20,000 wheel passes, regardless of being unweathered or weathered, indicating the weathering could have no significant effect on the moisture resistance of the four PEM mixes;
- The effect of weathering on the rubberized PEM mixes in the dry process and the wet process was higher than SBS control PEM, based on the rutting and Cantabro loss results; and
- Although the dry process and wet process PEM exhibited higher rut depth or Cantabro loss than control SBS PEM, no significant differences in field performance of PEM pavement were found; the dry process, the wet process, and the control PEM pavement exhibited excellent performance after three or five years’ service.

Acknowledgments

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Table 6. Air Voids of Core Samples

| Test section       | Average air voids of core samples (%) |
|--------------------|--------------------------------------|
| I-75 Valdosta, dry process | 18.6                                 |
| I-75 Valdosta, control     | 17.1                                 |
| I-75 Perry, dry process    | 16.8                                 |
| I-75 Perry, control        | 18.3                                 |

Fig. 10. Cantabro loss of PEM core samples
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