Florida Department of
TRANSPORTATION

THE EFFECT OF BINDER TYPE AND LAYER THICKNESS ON THE LONG-TERM PERFORMANCE OF OPEN-GRADED FRICTION COURSES

DOT Office

State Materials Office

Authors

Ohhoon Kwon

James Greene

Bouzid Choubane

Gregory Sholar

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EXECUTIVE SUMMARY

To improve the long-term durability and functionality of open-graded friction courses (OGFC), the Florida Department of Transportation (FDOT) investigated the use of a highly modified asphalt binder and increased thickness using Accelerated Pavement Testing (APT). A total of six test sections with combinations of two modified binder types (PG 76-22 and PG 82-22) and three lift thicknesses (0.75, 1.25, and 2 inches) were constructed at FDOT's APT facility. Accelerated loading was performed using a Heavy Vehicle Simulator (HVS) to evaluate the relative rutting performance of the test sections. Supplementary field and laboratory tests to identify tensile strength, Cantabro loss, field permeability, surface characteristics, and asphalt binder properties were also conducted. Test results indicated that the use of PG 82-22 polymer modified asphalt (PMA) binder might be beneficial in improving the long-term durability of the OGFC. Thicker layers of OGFC were found to have considerably less durability. It is recommended that the use of a highly modified PMA asphalt binder in OGFC layers be considered when raveling and other durability issues are of concern

1 INTRODUCTION

Conventional pavement systems drain precipitation from the surface by constructing the appropriate cross-slope and grade. However, geometry alone is inadequate to effectively drain the short-term and intense rainfall often observed in Florida. Heavy rainfall, therefore, occasionally overflows the pavement surface and overcomes the pavement surface micro texture, disrupting adhesion between the tire and pavement surface. Accordingly, this scenario yields a greater chance of hydroplaning and splash/spray *(1, 2).*

With driver safety being a top priority, many states have implemented the use of open-graded friction courses (OGFC) to effectively drain surface water. The interconnected air voids and greater macro texture of OGFC mixtures drain the surface water under heavy rainfall and minimize splash/spray and hydroplaning potential by diminishing the water membrane between tire and pavement surface *(1, 2, 3, 4, 5, 6).* Furthermore, multiple studies have found that the interconnected air voids in the OGFC layer reduce the tire-pavement interaction noise. Hence, the OGFC is also believed to be a quieter pavement *(5, 6, 7, 8).*

Starting in the mid-1970s, FDOT developed and implemented a 3/8-inch nominal maximum aggregate size (NMAS) OGFC mixture. This OGFC mixture was referred to as an FC-2 and was placed with a 0.5-inch layer thickness. Later, in the late1990s, a 1/2-inch NMAS OGFC mixture named FC-5 was developed that is placed at a 0.75-inch layer thickness. The FC-5 mixture has been in use for more than 20 years *(1).* Florida places OGFC mixtures on all multi-lane highways with a design speed of 50 mph or higher. Of the approximately 44,000 lane miles of pavement managed by FDOT, an OGFC surface is required on nearly half.

Despite the benefits, OGFCs have been found to have a relatively short service life compared to dense-graded friction courses. A continuous reduction in drainage capability has also been reported with the use of OGFCs *(2).* According to the last 20 years of pavement condition data collected by FDOT, the time at which the condition triggers rehabilitation of OGFCs is approximately 14 years as compared to approximately 18 years for dense-graded mixtures. It should also be noted that considerable variability in OGFC service life has been observed on

Florida roadways primarily due to rapid deterioration often associated with raveling *(9)*. OGFC mixtures are more susceptible to aging due to the greater interconnected air voids, which accelerate the reduction in structural stability and service life due to raveling and cracking *(2)*. In addition, the OGFC mixtures have been found prone to being clogged by dust, drained binder, dislodged aggregate particles, tack coat, and wheel path densification. As a result, OGFC mixtures may lose functionality with use and time *(1, 2, 8)*.

Reduced long-term performance of the FC-5 mixtures in terms of durability and functionality led FDOT to investigate the impact of PG 82-22 polymer modified asphalt (PMA) binder on the rutting resistance and durability of FC-5 mixtures. The implementation of PG 82-22 PMA binder for localized areas with the historical poor performance of dense-graded mixtures was found to be successful in a previous study conducted at FDOT's APT facility *(10)*. Despite the specified layer thickness of 0.75 inches for FC-5 mixtures, it is not uncommon for FC-5 surfaces to be placed thicker due to a variety of construction and design issues. While the thicker OGFC could be expected to provide a faster draining surface layer, thicker sections that ravel become more problematic and pose a safety and windshield risk due to the potential for deeper raveling. Consequently, a full-scale experiment with supplementary field and laboratory tests were conducted at FDOT's APT facility to assess the relative performance of FC-5 using PG 82-22 PMA binder and increased layer thickness under closely simulated in-service conditions.

2 OBJECTIVE AND SCOPE

The primary objective of this study was to investigate the relative performance of FC-5 mixtures using PG 82-22 PMA binder and increased thickness as compared to the standard specified binder and thickness. Two binders (PG 76-22 PMA and PG 82-22 PMA) and three design thicknesses (0.75, 1.25, and 2 inches) were considered in this study. A total of six full-scale test sections were constructed with combinations of the two binders and three thicknesses. The test section using PG 76-22 PMA binder and 0.75-inch layer thickness served as a control. A Heavy Vehicle Simulator (HVS) was used to investigate the rutting and durability of the test sections. Supplementary field and laboratory measurements, including indirect tensile strength, permeability, macrotexture, friction coefficient, and Cantabro loss test, were conducted to evaluate the functionality of the test sections in addition to supporting the APT results.

3 EXPERIMENTAL DESIGN

3.1 Construction of Test Sections

Two 12-foot wide by 450-foot-long lanes were milled and resurfaced as part of this study. Each lane consisted of three test sections. Two 1.5-inch lifts of a 12.5 mm nominal maximum aggregate size (NMAS) dense-graded Superpave mixture were placed on the milled surface as a structural course. Then, FC-5 mixtures using either PG 76-22 PMA or PG 82-22 PMA binder were placed in layer thicknesses of 0.75, 1.25, and 2.0 inches. All relevant FDOT construction specifications were followed. Figure 1 shows the cross-section design of the test sections.

Figure 1. Cross-section design of the test sections

3.2 Experimental Design

Accelerated loading was performed using FDOT's HVS to evaluate the rutting performance of the various FC-5 test sections. Each loading area was trafficked with unidirectional passes of a super single tire (Goodyear G286 A SS, 425/65R22.5) with 4-inches of wheel wander. A total of 100,000 passes of the 9-kip HVS wheel load were applied under a controlled temperature of 50°C at 2 inches below the pavement surface measured with embedded thermocouples. Rut-depth measurements of three loading areas assigned to each test section were averaged to compare the rutting performances of the test sections. Figures 2 and 3 show the test section layout and FDOT's HVS utilized for the evaluation of the rutting performance.

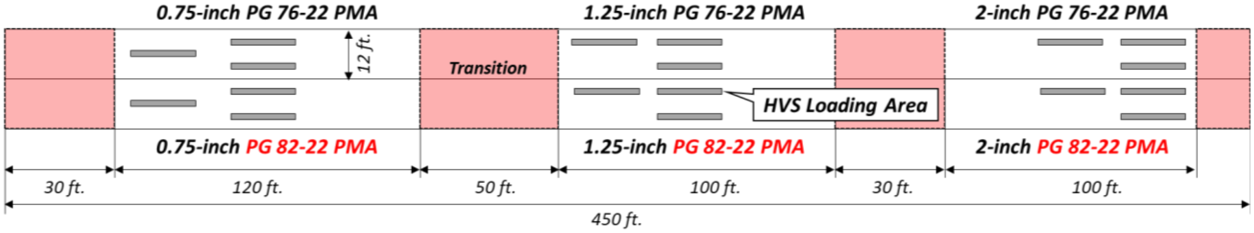

Figure 2. Test section layout and HVS loading areas

Figure 3. HVS used for accelerated loading in FDOT's APT facility

Indirect tensile strength and Cantabro loss tests were used to identify relative cracking and raveling performances, respectively *(11, 12)*. Three 4-inch cores were retrieved at randomly selected locations of the test sections with 2-inch in OGFC thickness. Those cores were trimmed to obtain 4-inch by 1.5-inch cylindrical OGFC specimens. Specific sample preparation and testing procedures are described later in this paper.

Permeability and surface properties were characterized using the falling head permeameter, circular track meter (CTM), and dynamic friction tester (DFT). Reductions in the functionality of the test sections due to traffic densification were also investigated by comparing test results before and after accelerated loading. Table 1 summarizes field and laboratory tests conducted for the subject study.

Table 1. Summary of Testing Methods for the OGFC Performance Evaluation.

Performance	Measurement (Testing Device)	Performance Comparison	Specifications
Rutting	Rut-depth (HVS)	Results of three replicate tests were averaged	N/A
Cracking	Indirect Tensile Strength (Pine AF850T)		ASTM D6931
Raveling	Cantabro Loss (LA Abrasion Machine)		AASHTO TP108
Surface Characteristics	Mean Profile Depth (MPD) (CTM)	Result of nine replicate tests (3 loading areas × 3 locations) were averaged	ASTM E2157
	Friction Coefficient (DFT)		ASTM E1911
Drainage Capability	Drainage Time (Falling Head Permeameter)		N/A

4 MATERIAL PROPERTIES

The PG 76-22 and PG 82-22 PMA binders used for the OGFC mixes were sampled from the asphalt mix plant. Both binders were formulated with an identical base binder (PG 67-22) and polymer modifier (Styrene-butadiene-styrene [SBS]), but with different dosage rates. The SBS content in PG 76-22 PMA binders is typically in the range of 2.0 to 2.5% by weight of the base binder, whereas the SBS content in PG 82-22 PMA binders is typically in the range of 3.0 to 3.5% *(10).* Both binders are allowed to contain polyphosphoric acid (PPA) as a co-modifier by FDOT’s standard specification. FC-5 aggregate from a granite stockpile was used for both OGFC mixes. To confirm the job mix formula (JMF), aggregate gradation of the mix samples from the delivery trucks was tested.

4.1 Dynamic Shear Rheometer (DSR)

The DSR test measures complex modulus (G*) and phase angle (δ) of asphalt binder to characterize the viscous and elastic behavior. G*/sinδ at high temperature is considered a rutting performance indicator, whereas G*·sinδ at an intermediate temperature is believed to indicate fatigue performance. Original binder samples were prepared to determine the G*/sinδ, while conditioned binder samples with rolling-thin film oven (RTFO) and pressure aging vessel (PAV) were used to identify the G*·sinδ.

Figure 4 summarizes DSR test results for comparing rutting and fatigue cracking potentials of the mixes using both binders. The higher G*/sinδ and lower G*·sinδ values observed for the PG 82-22 PMA binder imply that the PG 82-22 PMA binder behaves more elastic-solid at the high temperature and elastic-soft at the intermediate temperature, respectively *(13)*. With the DSR test results, it can be speculated that the OGFC mix using PG 82-22 PMA binder has better rutting and fatigue resistance than the one with PG 76-22 PMA binder.

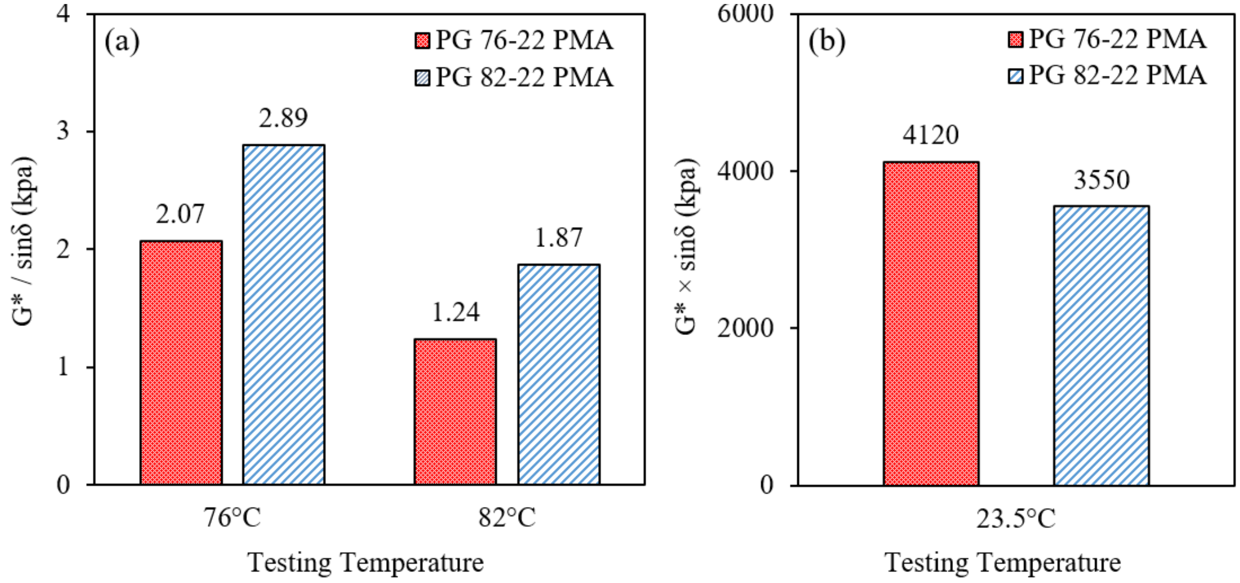

Figure 4. Comparisons of (a) G*/sinδ and (b) G*·sinδ

4.2 Multiple Stress Creep Recovery

Both PG 76-22 and PG 82-22 PMA binder samples were conditioned in the RTFO in accordance with AASHTO M332. Then, Multiple Stress Creep Recovery (MSCR) tests were performed at a testing temperature of 67°C as specified in FDOT's standard specification. The non-recoverable creep compliance (Jnr) obtained from the MSCR test relatively evaluates the rutting performance of a mix with the tested binder. A study conducted by the Federal Highway Administration (FHWA) concluded that a reduction of 50% in Jnr may reduce roadway rutting by 50% and APT rutting by 30 to 40% *(10, 14)*. Also, the percent recovery measured in the same test shows the elastic response of the binder sample. The greater percent recovery at the high testing temperature implies the better rutting resistance of a mix using the sampled binder *(14)*. Table 2 summarizes MSCR test results and required binder properties for both PG grades in Florida. The PG 82-22 PMA binder exhibited greater elastic response and better rutting resistance potential than PG 76-22 PMA binder, as indicated by the percent recovery and Jnr values*)*.

Table 2. Summary of MSCR test results for both PG 76-22 and PG 82-22 PMA binders

Testing Temp.	MSCR Property	Binder Test Result		FDOT Specification	
		PG 76-22 PMA	PG 82-22 PMA	PG 76-22 PMA	PG 82-22 PMA
67°C	% Recovery, 3.2 kPa^{-1}	$66.41 \geq 40.25$	$90.37 \geq 63.65$	% $R_{3.2} \geq 29.37 \times (J_{nr,3.2})^{-0.2633}$	% $R_{3.2} \geq 29.37 \times (J_{nr,3.2})^{-0.2633}$
	J_{nr}, 3.2 kPa^{-1}	0.302	0.053	Max. 1.0 kPa^{-1}	Max. 0.5 kPa^{-1}
	J_{nr}, % Diff.	37.56	113.78	Max. 75% when $J_{nr} \geq 0.50$ kPa^{-1}	Max. 75% when Jnr ≥ 0.50 kPa^{-1}

4.3 Aggregate Gradation

Aggregate gradation was determined after burning off the asphalt binder of the mix samples obtained from the delivery trucks using the ignition oven. As presented in Figure 5, test results indicated that the gradations of the aggregates used in PG 76-22 and PG 82-22 PMA mixes were essentially identical.

Both gradations were slightly finer than the JMF but within the tolerance range specified in the FDOT's standard specification.

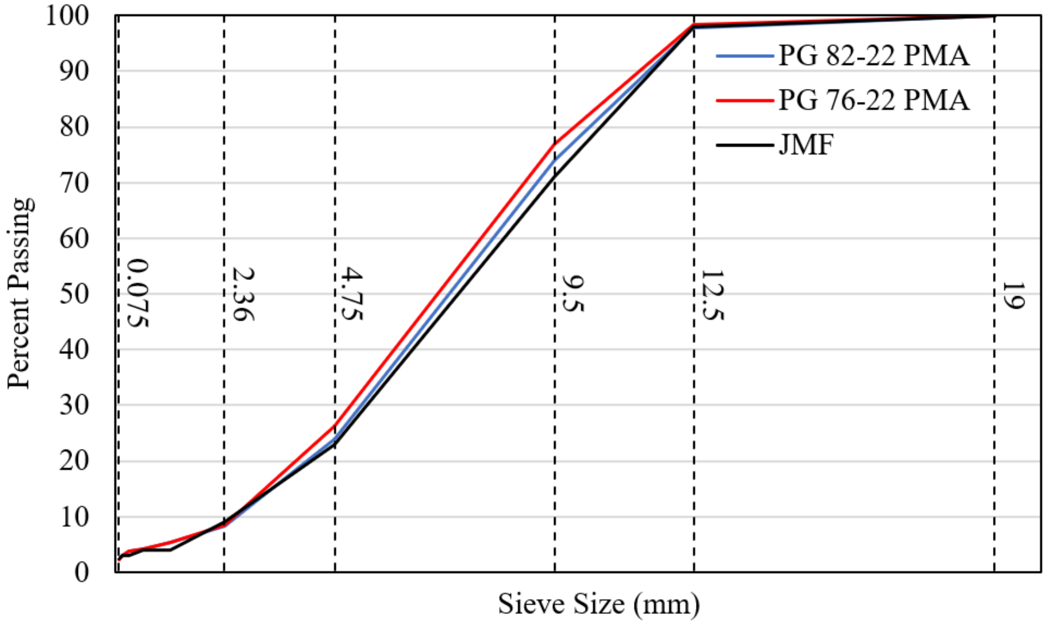

Figure 5. Comparisons of aggregate gradation for both OGFC mixes

5 TEST RESULT AND ANALYSIS

5.1 OGFC Durability

5.1.1 Rutting Resistance

Each loading area was trafficked with unidirectional passes of a super single tire with 4-inches of wheel wander. A total of 100,000 passes of the 9-kip HVS wheel load were applied under a controlled temperature of 50°C at 2 inches below the pavement surface. Rut-depths were measured by the laser profiler installed underside of the HVS wheel carriage at predetermined HVS pass numbers. Rut-depths from three replicate loading areas within a test section were averaged and plotted in Figure 6. As presented, thicker OGFC sections exhibited greater rut-depths for both PG 76-22 PMA and PG 82-22 PMA mixes. In addition, test sections with PG 82-22 PMA showed 6% to 30% reduced rut-depths than those of corresponding PG 76-22 PMA sections.

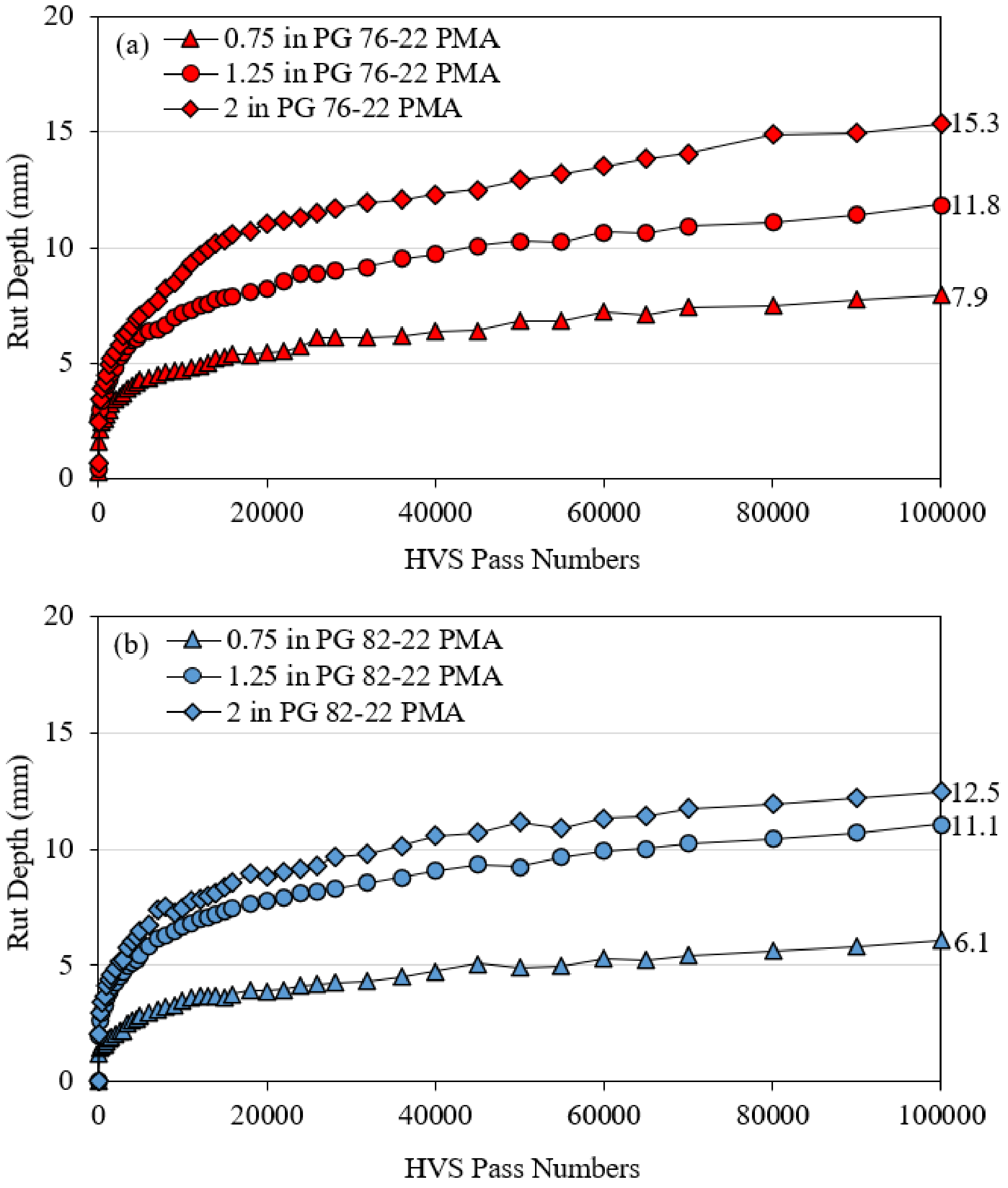

Figure 6. Comparison of rut-depth of test sections using (a) PG 76-22 PMA and (b) PG 82-22 PMA binder

The thickness of the FC-5 and structural course was assessed to identify the primary contributor to the rut-depth observed in the test sections. Three cores were taken at loaded and unloaded areas of each test section to determine the densification caused by the 100,000 HVS wheel passes. Figure 7(a) shows cores retrieved in a test section, and Figure 7(b) compares the layer thickness of the corresponding cores. Figure 8 shows the average core thickness of all test sections. As presented, the thickness of the OGFC layers was reduced by 14% to 39%, while negligible thickness changes were observed in the structural layers. The test result indicated that the OGFC layer was the primary contributor to the rutting observed in the subject study. Also, the OGFC with PG 82-22 PMA binder demonstrated greater rutting resistance than the corresponding PG 76-22 PMA sections.

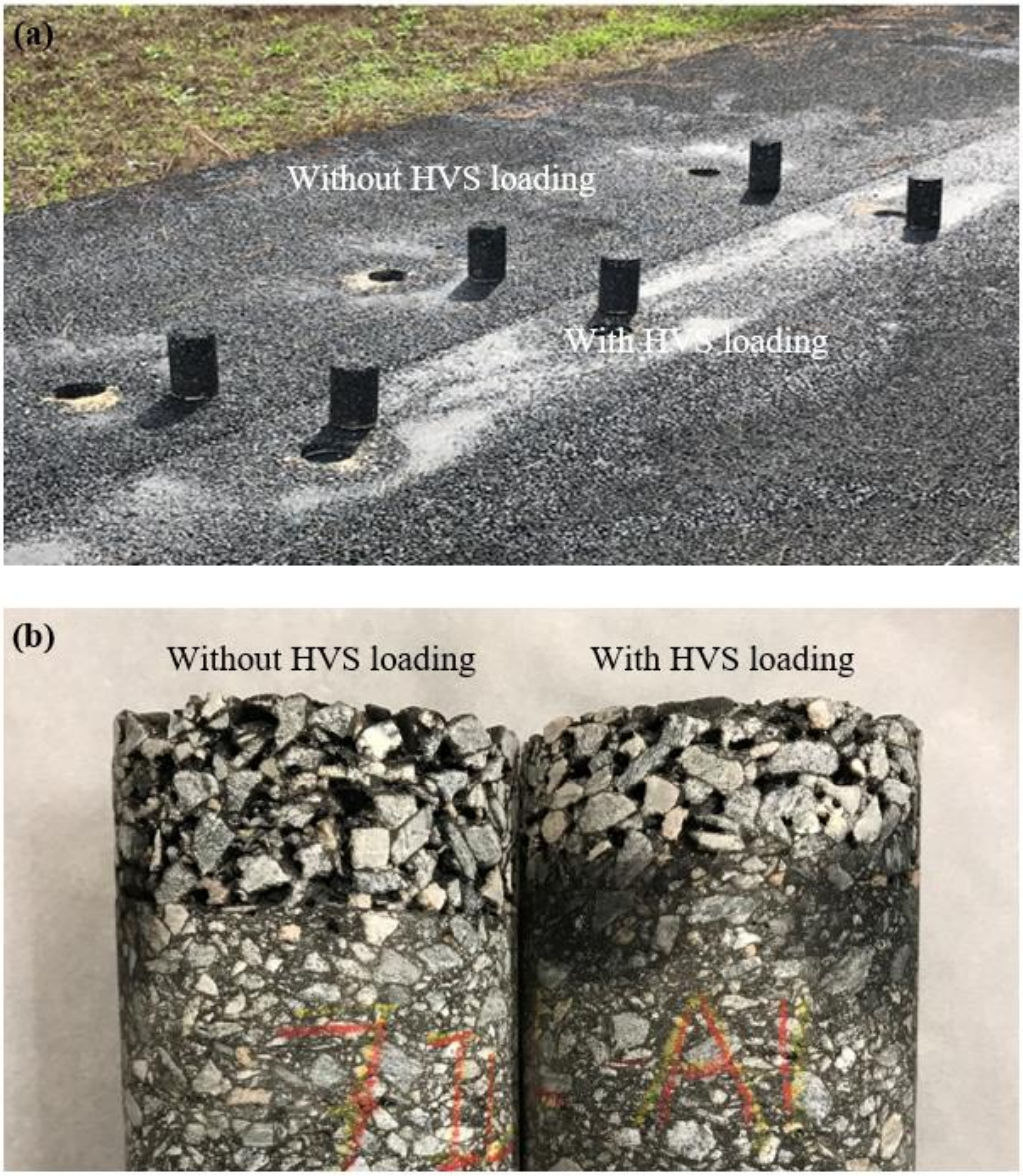

Figure 7. (a) Cores taken from the 2-inch PG 76-22 PMA section and (b) comparison of thickness changes

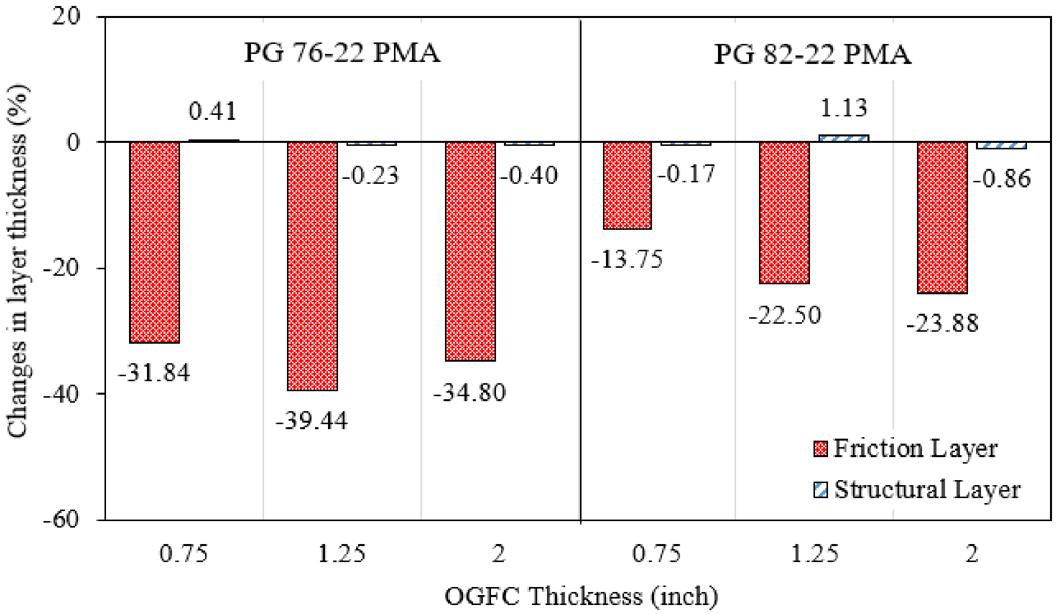

Figure 8. Comparison of thickness changes

5.1.2 Cracking and Raveling Resistance

The indirect tensile strength of three 4-inch core specimens obtained at randomly selected locations on each of the 2-inch test sections was tested to identify relative cracking performances *(11, 12)*. The 0.75 and 1.25-inch sections were excluded from the strength test since the thicknesses of the OGFC did not meet the minimum specimen height of 1.5-inch specified in ASTM D6931. As presented in Figure 9 (a), the core specimens from the PG 82-22 PMA section showed approximately 45% greater tensile strength than those from the PG 76-22 PMA section. The test results indicate that the use of PG 82-22 PMA binder for the OGFC mix may provide better cracking resistance *(11, 12)*.

Similarly, three 4-inch cores were retrieved at randomly selected locations on each of the 2-inch test sections. The cores were trimmed to obtain 4 -inch by 1.5-inch cylindrical OGFC specimens. Cantabro loss was measured after 180 revolutions of the LA abrasion drum instead of the 300 revolutions specified in AASHTO TP 108. Applying the reduced number of revolutions was to prevent the disintegration of the thin core specimens observed in trial tests. Figure 9 (b) compares average Cantabro abrasion losses of the PG 76-22 and PG 82-22 PMA mixes. Test results clearly show that the OGFC mix with PG 82-22 PMA binder exhibited less aggregate loss under identical revolutions of the LA abrasion drum. This implies that the use of PG 82-22 PMA produces better raveling resistance than the PG 76-22 PMA mix.

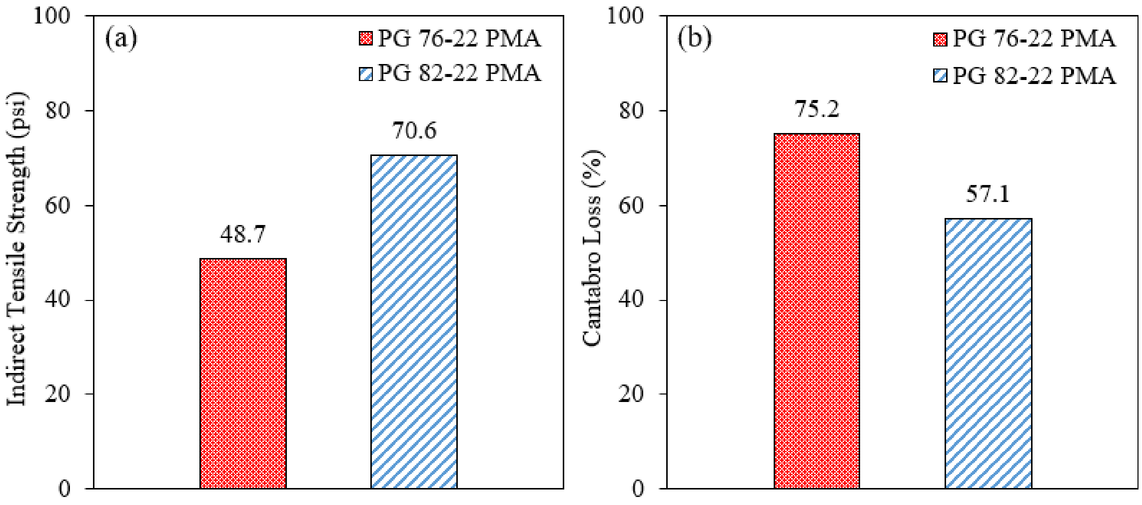

Figure 9. Comparison of (a) indirect tensile strength and (b) Cantabro abrasion loss

5.2 OGFC Functionality

Non-destructive tests to measure field permeability, macrotexture, and friction coefficient were utilized to evaluate the functionality of the OGFC test sections. As presented in Figure 10, three test locations were assigned to each loading area, and three replicate tests were performed at each test location. A total of 27 measurements obtained from the three loading areas in a test section were averaged to compare the functional performance of the test sections. Also, the non-destructive tests were performed before and after accelerated loading to identify the reductions in the functional performances due to the traffic densification.

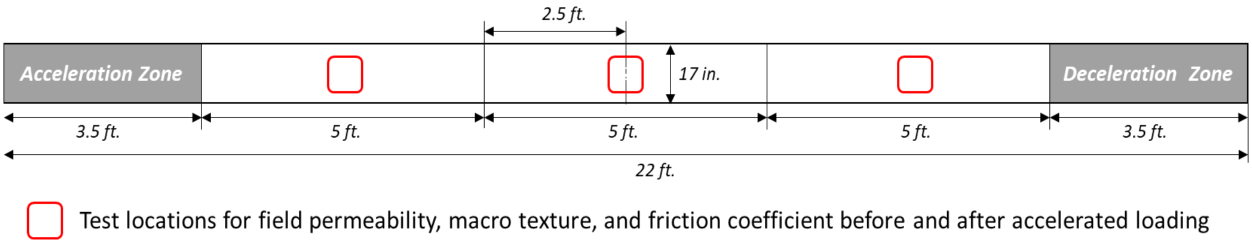

Figure 10. Comparison of (a) indirect tensile strength and (b) Cantabro abrasion loss

5.2.1 Drainage Capability

One of the primary benefits of the OGFC is draining the surface water through the interconnected air void and significantly reducing the chance of hydroplaning and spray/splash. The drainage capability of the OGFC was quantified by measuring the drainage time of the water from the top to bottom mark of the falling head permeameter presented in Figure 11. The water in the container drains only through the interconnected air void of the OGFC since a thick, soft sealing material pressed by two 40-pound weights seals the gaps between the bottom plate and the pavement surface. Thus, the drain time is highly related to the drainage capability of the OGFC layer. The shorter drain time represents faster drainage of surface water.

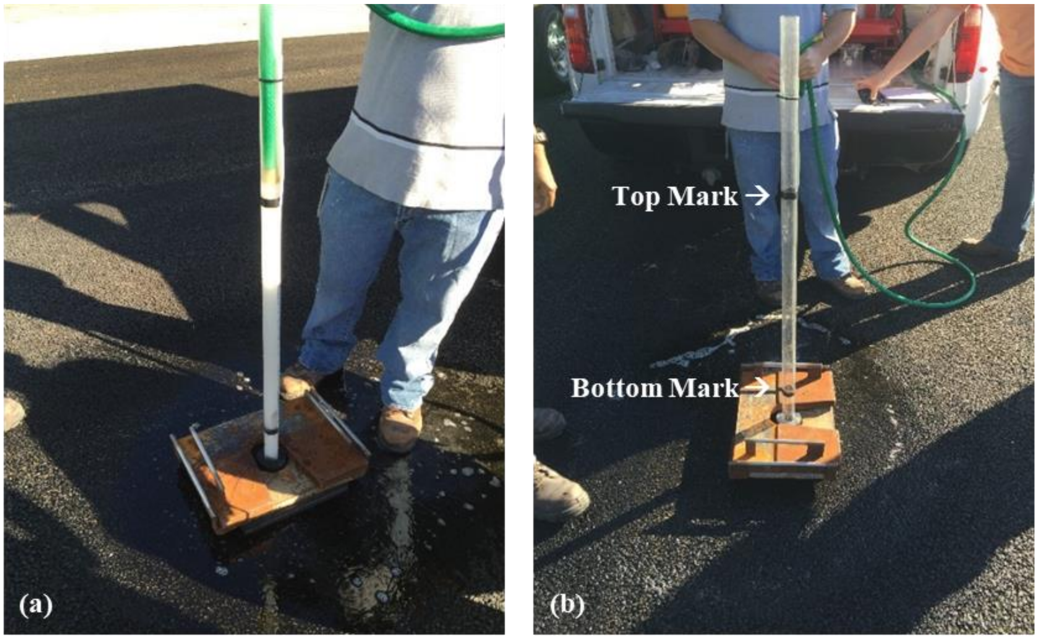

Figure 11. FDOT's falling head permeameter: (a) water filling and (b) measuring drain time

Figure 12 compares average drainage times between test sections (a) before and (b) after application of the 100,000 HVS wheel passes. Initially, the drainage time of most test sections was comparable. However, after HVS loading, test sections using PG 82-22 PMA binder showed relatively shorter drainage time than the corresponding PG 76-22 PMA sections. The test result indicates that the use of PG 82-22 PMA binder helps to resist the reduction of interconnected air-void due to the wheel-path densification. It is also noted that faster drainage time was anticipated on the thicker OGFC sections due to the increased storage capacity. However, no clear trends were observed between the layer thickness and drainage time.

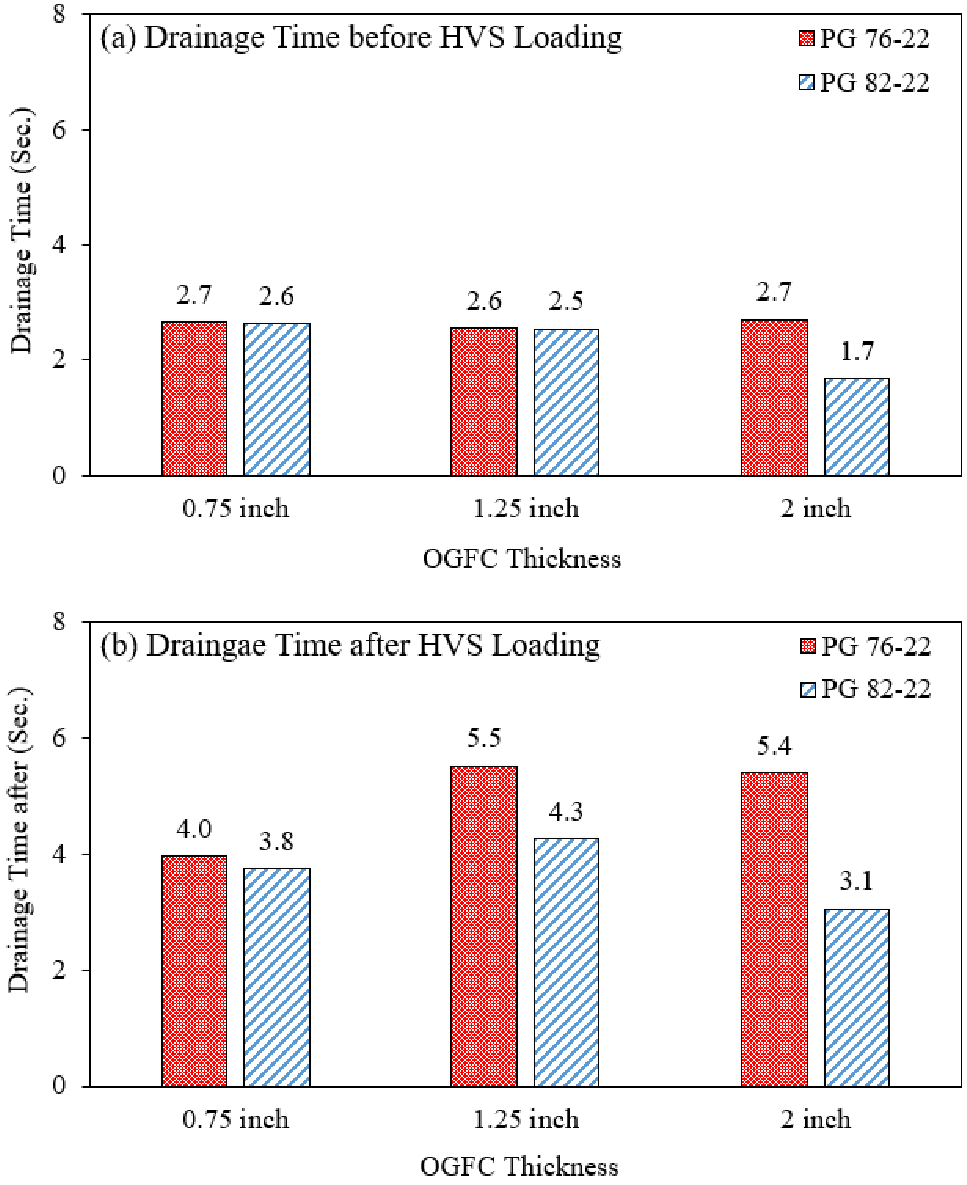

Figure 12. Comparisons of drainage time

5.2.2 Surface Characteristics

The surface characteristics of the test sections were characterized by the mean profile depth (MPD) and friction coefficient. Those measurements are critical parameters when considering the chance of hydroplaning and wet-skid resistance of a pavement. Pavement surfaces with greater MPD and friction coefficients may provide less chance of hydroplaning and greater wet skid resistance *(7).*

The MPD and friction coefficient were measured on the 0.75-inch sections. It was assumed that the OGFC thickness had no relationship to these surface characteristics since raveling was not observed on any of the test sections. Replicate tests were performed before and after HVS loading to identify the reductions in MPD and friction coefficient due to the surface wearing/ polishing of the OGFC. Figure 13 shows the CTM and DFT utilized in this study.

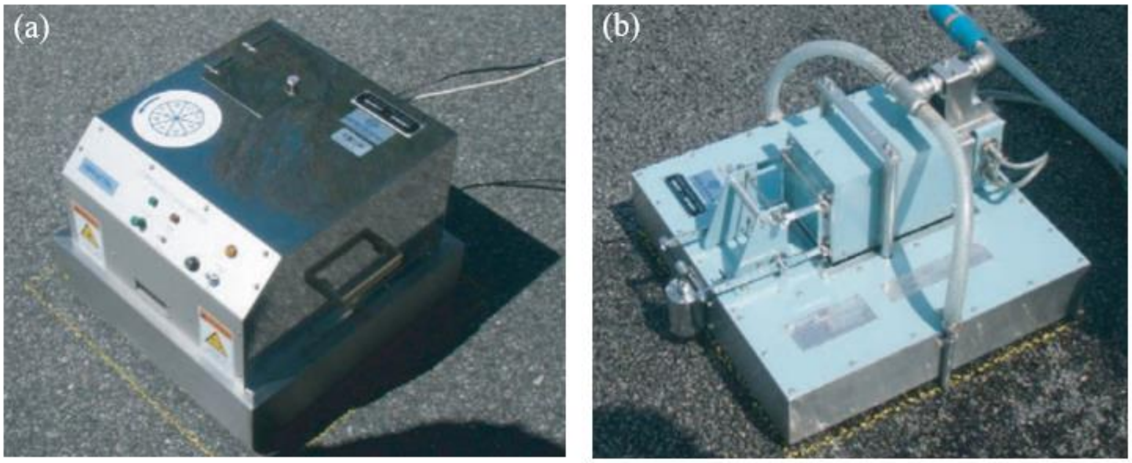

Figure 13. (a) CTM and (b) DFT utilized to characterize surface properties

Figure 14 (a) shows average MPDs for both PG 76-22 PMA and PG 82-22 PMA sections before and after HVS loading. Considering the precision of replicate MPD readings, both test sections showed comparable MPDs before and after accelerated loading. Figure 14 (b) compares average friction coefficients at 60 km/h. Initially, identical friction coefficients were observed in both test sections. However, friction coefficients dropped by more than 20% after the application of the HVS for both test sections. Polishing of the surface aggregate, but limited to the micro texture, may cause a reduction in friction coefficient. The test result indicates that the binder type did not affect the macro-texture and friction coefficient.

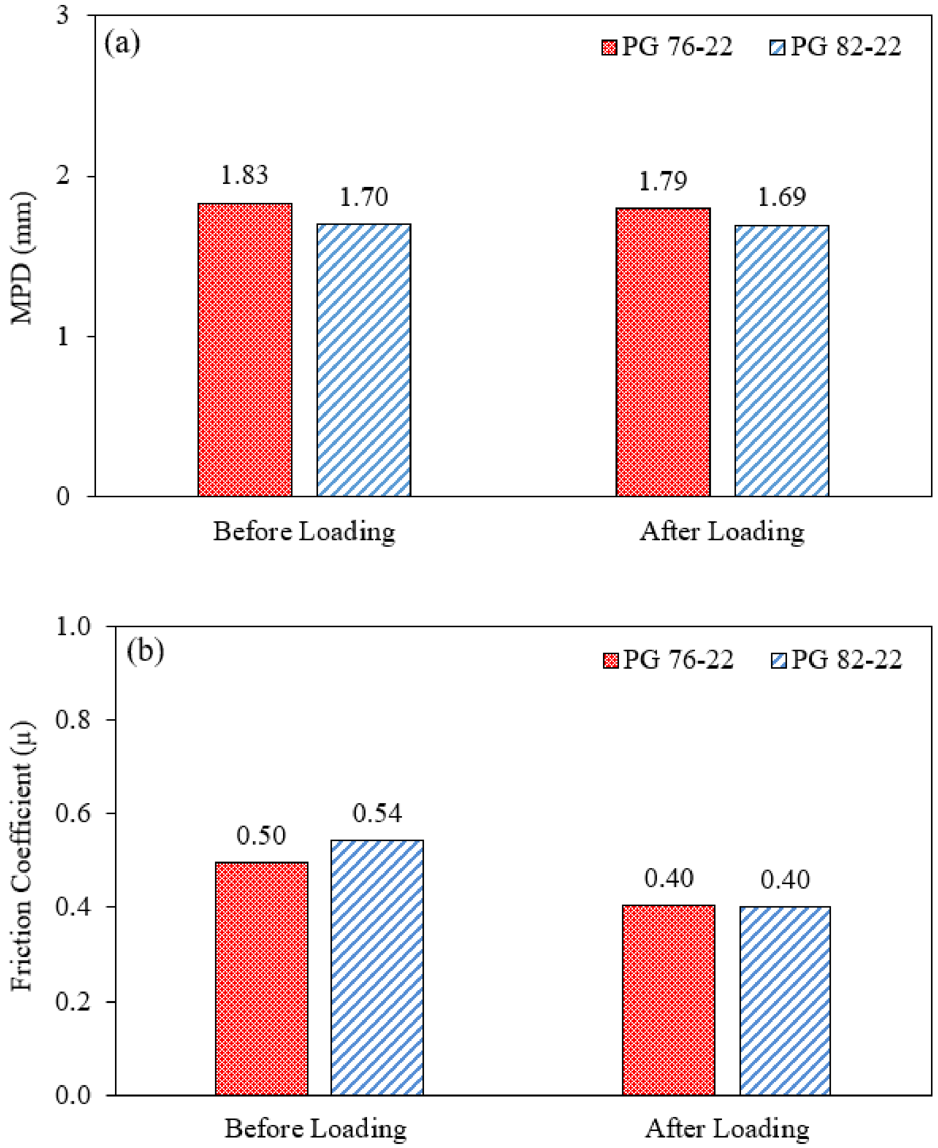

Figure 14. Comparison of (a) MPDs and (b) friction coefficients before and after HVS loading

6 SUMMARY AND CONCLUSION

This paper documents and summarizes an experimental investigation of the impact of PG 82-22 PMA and increased layer thickness on FC-5 mixtures. In general, FC-5 test sections and mixtures with PG 82-22 PMA were found to be more rut resistant, crack resistant, and durable. Increasing the thickness of FC-5 layers was found to accelerate rutting and provided less durable mixtures. Specific findings of this research are summarized as follows:

- Under identical loading conditions, significantly better rutting resistance was observed in the test sections with the standard 0.75-inch FC-5 thickness compared to thicker applications. Sections with PG 82-22 PMA were found to have slightly better rut resistance than those with PG 76-22 PMA, particularly for sections placed at 0.75 and 2inch thick. In addition, the OGFC thicknesses were decreased by 14% to 39% due to densification from the accelerated loading, whereas negligible thickness changes were observed in the structural layer.

- On average, core specimens from the PG 82-22 PMA specimens showed approximately 45% greater indirect tensile strength and 30% lower Cantabro loss than those of the PG 76-22 PMA specimens. With the test results, it can be postulated that the OGFC mix with the PG 82-22 PMA binder provides improved raveling resistance.

- Initially, neither different binders nor OGFC thicknesses significantly affect the drainage time. However, after the 100,000 HVS wheel passes were applied, test sections using PG 82-22 PMA binder showed relatively faster drainage time than those of the PG 76-22 sections. This is likely due to less deformation of the layer due to slightly better rut resistance.

- MPD and friction coefficients of the PG 76-22 and 82-22 PMA sections were comparable. For both test sections, friction coefficients were reduced by more than 20% with the application of the 100,000 HVS wheel passes due to the polishing of the surface materials, while negligible MPD changes were observed.

7 ACKNOWLEDGEMENTS

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