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Evaluation of 4.75-mm Nominal Maximum Aggregate Size (NMAS) Mixture Performance Characteristics to Effectively Implement Asphalt Pavement System

4.75 mm 공칭 최대 골재 치수 아스팔트 혼합물의 효과적인 포장 시스템 적용을 위한 공용성 특성 평가 연구

Chun, Sanghyun	천상현	Member · Univ. of Florida Postdoctoral Research Associate · Corresponding Author (E-mail : shchun@ufl.edu)
Kim, Kukjoo	김국주	Univ. of Florida Graduate Research Assistant (E-mail : klauskim@ufl.edu)
Park, Bongsuk	박봉석	Univ. of Florida Graduate Research Assistant (E-mail : bongsuk@ufl.edu)

ABSTRACT

PURPOSES : This study primarily focused on evaluating the performance characteristics of 4.75-mm nominal maximum aggregate size (NMAS) asphalt mixtures for their more effective implementation to a layered flexible pavement system.

METHODS : The full-scale pavements in the FDOT's accelerated pavement testing (APT) program, including 4.75-mm mixtures at the top with different thicknesses and asphalt binder types, were considered for the faster and more realistic evaluation of the rutting performance. The results of superpave indirect tensile (IDT) tests and hot-mix asphalt fracture mechanics (HMA-FM) based model predictions were used for cracking performance assessments.

RESULTS : The results indicated that the rutting performance of pavement structures with 4.75-mm mixtures may not be as good as to those with the typical 12.5-mm mixtures, and pavement rutting was primarily confined to the top layer of 4.75-mm mixtures. This was likely due to the relatively higher mixture instability and lower shear resistance compared to 12.5-mm mixtures. The energy ratio (ER) and HMA-FM based model performance prediction results showed a potential benefit of 4.75-mm mixtures in enhanced cracking resistance.

CONCLUSIONS : In relation to their implementation, the best use of 4.75-mm mixtures seem to be as a surface course for low-traffic-volume applications. These mixtures can also be properly used as a preservation treatment that does not necessarily last as long as 12.5-mm NMAS structural mixes. It is recommended that adequate thicknesses and binder types be considered for the proper application of a 4.75-mm mixture in asphalt pavements to effectively resist both rutting and cracking.

Keywords
accelerated pavement testing (APT), flexible pavement, 4.75-mm NMAS asphalt mixtures, cracking and rutting performance

Corresponding Author : Chun, Sanghyun, Postdoctoral Research Associate
Engineering School of Sustainable Infrastructure and Environment,
University of Florida, P.O. Box 116580, 365 Weil Hall, Gainesville,
FL 32611, USA
Tel : +1.352.672.3972 Fax : +1.352.392.1660
E-mail : shchun@ufl.edu

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1. INTRODUCTION

1.1. Background

During the last decades, the use of 4.75 mm Nominal Maximum Aggregate Size (NMAS) asphalt mixtures has become increasingly popular due to its significant benefits on improving cost efficiency and functionality as an effective surface paving alternatives. This type of fine mixes enables the application of a thin lift which indicates a great potential for use in preventive maintenance program. This thin lift is able to retrieve ride quality and also has advantages for providing leveling courses to reduce construction time. Also, it was widely reported from diverse research studies that 4.75 mm NMAS mixtures may result in increased durability, reduced permeability, and tire-pavement noise (Li et al. 2012; Lu and Harvey 2011; Rahman 2010).

Previous research conducted by the National Center for Asphalt Technology (NCAT) has developed and refined the Superpave mix design criteria for 4.75 mm NMAS mixtures based on laboratory and field evaluation (Cooley Jr et al. 2002; West et al. 2010). In response, the American Association of State Highway and Transportation Officials (AASHTO) added these mixes to the Superpave mix design system. The Florida Department of Transportation (FDOT) along with other state agencies has implemented 4.75 mm mixtures for use in a possible leveling and patching materials, a thin-overlay and a crack relief layer, especially for low traffic volume road applications with reduced cost and construction time. However, these applications are fairly new concept with limited local experiences and information. Also, due to the nature of such a fine mixture, potential concerns still exist including rutting, moisture damage, and frictional resistance with smooth surface texture (Cantrell 2013; Dowan and Sungho 2015; Jongeun et al. 2015; Son et al. 2013). Therefore, a thorough evaluation of 4.75 mm mixture performance is needed to further develop this mix for enhanced structural capacities, rutting and cracking resistance in order to fully implement the Superpave system. This also helps provide an effective application of 4.75 mm NMAS thin overlay as a surface course for asphalt pavements.

This paper will include a complete description of the rutting and cracking performance evaluation of 4.75 mm NMAS asphalt mixtures as compared to those of 12.5 mm NMAS mixtures. The accelerated pavement testing (APT) was considered to allow for a faster and a more practical assessment of rutting performance. For cracking performance evaluation, laboratory mixture testing was conducted using the Superpave Indirect Tension (IDT) tests. In particular, to quantify the mixture cracking resistance, Hot-Mix Asphalt fracture mechanics (HMA-FM) based model in conjunction with the Superpave IDT test results were used for cracking performance analysis (Roque et al. 2002; Zhang et al. 2001).

1.2. Objectives and Scope

The primary objective of this study is to evaluate the performance characteristics of 4.75 mm NMAS asphalt mixtures for both rutting and cracking to determine the effect and proper application of these mixes as a thin surface course for layered flexible pavement system. Rutting performance evaluation was conducted using APT. For APT rut evaluation, four experimental test pavement sections were constructed using a combination of different 4.75 mm layer thicknesses (i.e. 1.3 and 2.6 cm) and asphalt binder types (PG 67-22 and PG 76-22). Cracking performance evaluation was performed using laboratory tests and HMA-FM based model predictions for 4.75 mm mixtures with PG 67-22 and PG 76-22 binders. Also, 12.5 mm mixtures with PG 67-22 and PG 76-22 binders were evaluated for use as control mixes.

2. 4.75 mm NMAS ASPHALT MIXTURE

Since the concept of 4.75 mm NMAS mixture was introduced and adopted to the Superpave mix design system, many state agencies have implemented it for projects in consideration with the use of screenings to produce HMA mixture, low traffic volume road applications, leveling and patching, and thin overlays and surface mixtures. Primary advantages of these mixes include the capability of thin lift application, excellent smoothness, practically impermeable, good use of fine aggregate materials which are in surplus in many years, good use of fractioned fine reclaimed asphalt pavement (RAP) which helps improve the stability of 4.75 mm mixes, and good workability with hand tools. However, there are also latent limitations that include specific concerns of these mixes with respect to high asphalt contents, low frictional resistance due to the low surface texture of the mixtures, and greater potential for permanent deformation. High asphalt contents of 4.75 mm mixtures can be offset some by including fractioned RAP in the mix design. Also, a resistance to permanent deformation can be improved by designing mixes with lower Voids in Mineral Aggregate (VMA), using highly angular aggregates, RAP, and a stiffer polymer modified asphalt binder (PMA), and achieving good density and/or low in-place air voids during construction.

In general, owing to the nature of 4.75 mm mixture (i.e. mixture characteristics with smaller NMAS), these mixtures are prone to fail earlier under critical condition but hold up well for low stress and strain level. These mixes also exhibit less aggregate interlocking effect, decreased shear resistance, and therefore relatively greater rutting potential. On the contrary, mixtures with larger NMAS carry a greater load per particle and accentuate the stress concentration as well as show greater aggregate interlocking effect, enhanced resistance to shear deformation and fracture that result in better rutting performance expected. Cracking occurs in the brittle range (i.e. relatively small strain range), hence larger aggregate interlocking may not as critical as for a case of rutting. Table 1 summarizes the proposed design criteria for 4.75 mm NMAS Superpave design mixtures by NCAT (Cooley Jr et al. 2002; West et al. 2010).

Table 1. Proposed Design Criteria for 4.75 mm NMAS Superpave Mixtures

Design ESALs Range (million)	N_{des}	Min FAA	Min SE	Min V_{be}	Max V_{be}	% G_{mm} @ N_{ini}	D:B Ratio
< 0.3	50	40	40	12.0	15.0	≤ 91.5	1.0 to 2.0
0.3 to ≤ 3.0	75	45	40	11.5	13.5	≤ 90.5	1.0 to 2.0
3.0 to ≤ 30	100	45	45	11.5	13.0	≤ 89.0	1.0 to 2.0

Gradation limits		
Sieve size (mm)	Max	Min
12.5	-	100
9.5	100	95
4.75	100	90
1.18	30	55
0.075	13	6

Note : 1. Design V_a range = 4.0% - 6.0%

3. RUTTING PERFORMANCE EVALUATION

3.1. APT Rut Measurements

A total of four experimental test pavement sections were constructed including varied 4.75 mm mixture layer thicknesses (i.e. 1.3 and 2.6 cm) and binder types (i.e. PG 67-22 and PG 76-22) for surface course. Each test section consisted of 3.8 cm HMA lift of 12.5 mm fine graded Superpave mixture with PG 76-22 binder placed over an another 3.8 cm HMA lift of 12.5 mm fine graded Superpave mixture with PG 67-22 binder. Granite aggregates were used for all asphalt mixtures. The supporting layers included a 26.7 cm of limerock base and a 30.5 cm of stabilized subgrade with a mixture of limerock and native soil as indicated in Fig. 1. All test sections were constructed according to standard FDOT specifications.

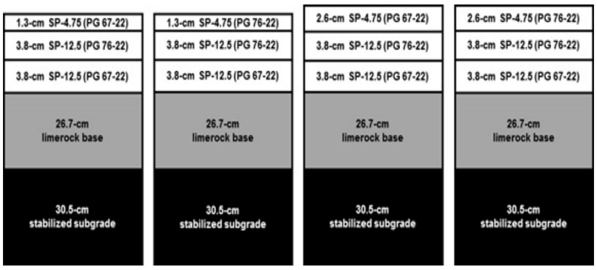
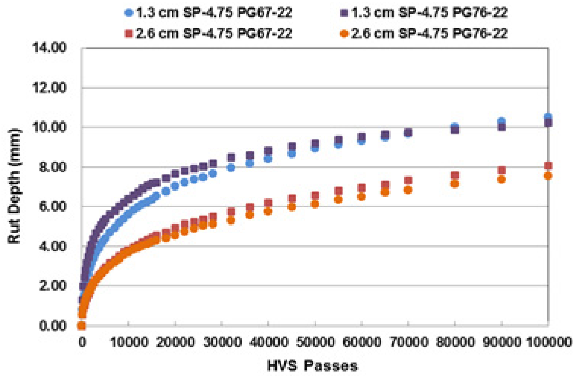


Fig. 1 APT Test Section Pavement Structures

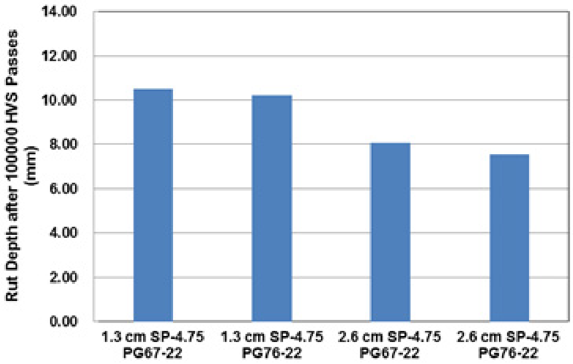
Accelerated loading was performed using FDOT's Heavy Vehicle Simulator (HVS) with a wide-base super single tire (Goodyear G286 A SS, 425/65R22.5) loaded to 40 kN and inflated to 689 kPa. Test sections were trafficked with a wheel wander of 5.1 cm and the test temperature was maintained at 50 ℃ during the tests. Insulated panels were attached to the HVS to keep required testing temperature. Fig. 2 shows the HVS and wide-base super single tire used. More detailed information of FDOT's APT facility is described elsewhere (Byron et al. 2004).

Fig. 2 HVS in FDOT's APT Facility

To normalize the effect of construction variability and different pavement aging times prior to testing, at least three tests were performed for each test section using a randomized test sequence. Rut depth measurements were conducted periodically using a laser profiling system mounted on the underside of the HVS carriage. Rut tests are typically terminated when a 1.3 cm rut depth is reached considered as failure, otherwise, tests are continued until a total of 100,000 HVS passes have been completed. Figs. 3 (a) and (b) represent the results of average rut progression and average rut depth after 100,000 HVS passes for each test lane, respectively. In general, rutting performance is likely not as good for pavement sections with 4.75 mm layer as compared to those with typical 12.5 mm layers without 4.75 mm lift as a surface course. Results indicate that the effect of 4.75 mm layer thickness appears more dominant than binder type for rutting performance. It was found that pavement sections with 2.6 cm of 4.75 mm mixture show relatively improved rutting resistance than those with 1.3 cm of 4.75 mm mixture and slightly better rutting performance was identified for sections with PG 76-22 binder than those with PG 67-22 binder.



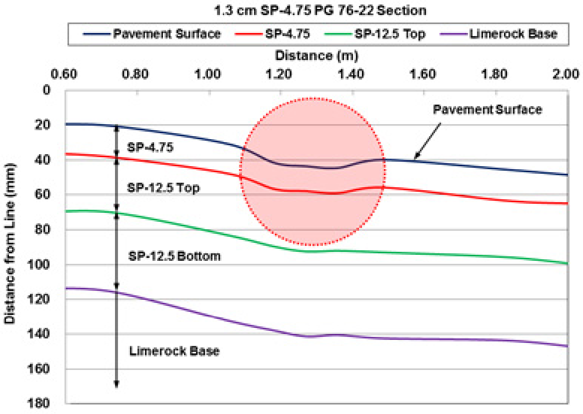
(a) APT Average Rut Profiles



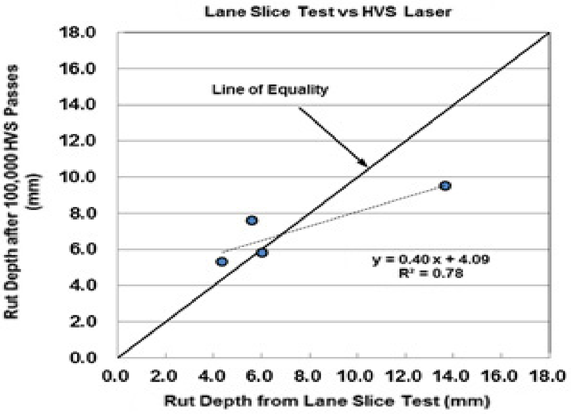
(b) APT Average Rut Depth After 100,000 HVS Passes

Fig. 3 APT Rut Measurements

In addition, lane slice tests were performed on one pavement sub-section from each test lane to determine primary source of rutting, which individual layer mostly contributes rut depths obtained from 4.75 mm sections evaluated. Results clearly indicate that a primary source of rutting is a 4.75 mm layer and rutting was mostly confined to 4.75 mm layer above the top 12.5 mm layer that may be associated with mixture instability and low shear resistance of 4.75 mm NMAS mixtures. Also, it is interesting to note that the rut depths measured from the cores for lane slice tests are roughly matched with those measured with HVS laser profile system. Fig. 4 (a) shows one example of the lane slice test result for 1.3 cm 4.75 mm section with PG 76-22 asphalt binder and Fig. 4 (b) exhibits relationship between rut depths from lane slice tests and HVS laser profile system.



(a) Lane Slice Test Result



(b) Lane Slice Test vs. HVS Laser Profile System

Fig. 4 Lane Slice Test Results for 4.75 mm Test Sections

4. CRACKING PERFORMANCE EVALUATION

4.1. Determination of Mixture Fracture Thresholds and Parameters

Fracture properties of asphalt mixtures required to evaluate cracking performance using HMA-FM based model were obtained from the Superpave IDT tests. The 4.75 mm NMAS mixtures with PG 67-22 and PG 76-22 binders as well as the 12.5 mm NMAS mixtures with PG 67-22 and PG 76-22 binders were tested as control mixes for evaluation. Tests were performed at 10 ℃ which have consistently been determined to correlate well with field cracking performance for asphalt pavements in Florida (Chun et al. 2012; Roque et al. 2004). All details of test procedure were introduced elsewhere (Roque et al. 1997). The Florida researchers have developed the energy-based fracture parameter termed energy ratio (ER) for use as an indicator of top-down cracking resistance of asphalt pavements and this parameter has been validated through diverse research projects (Roque et al. 2004; Roque et al. 2011). In general, the ER values are related to dissipated creep strain energy at failure ($DCSE_f$) and creep rate of asphalt mixtures. The detailed information of the ER parameter can be found elsewhere (Roque et al. 2004). Higher ER values required for better cracking performance can be achieved by minimizing a creep rate but maintaining a $DCSE_f$. Fig. 5 defines how the DCSE threshold can be determined using the stress-strain response obtained from the Superpave IDT strength test. Where, M_R = resilient modulus, ε_f = failure strain, D_1 and m = power law parameters from creep compliance test, $a = 0.0299\sigma^{-3.1}(6.36 - S_t) + 2.46 \times 10^{-8}$ in which, σ = tensile stress of asphalt layer in psi and S_t = tensile strength in MPa.

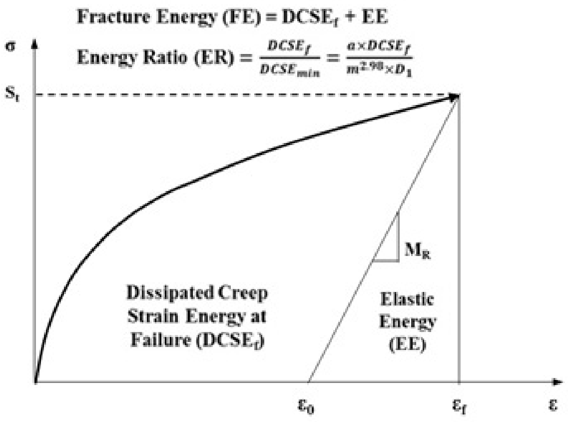
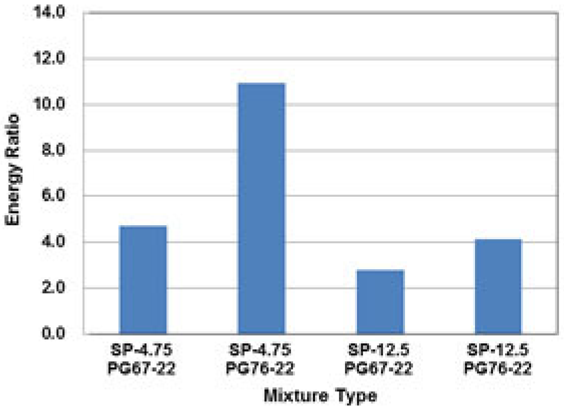
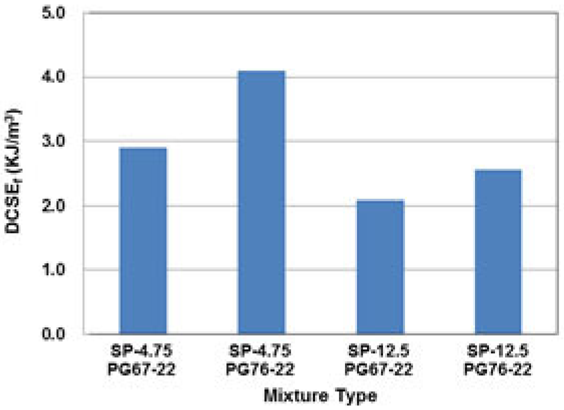


Fig. 5 Determination of DCSE and FE Threshold

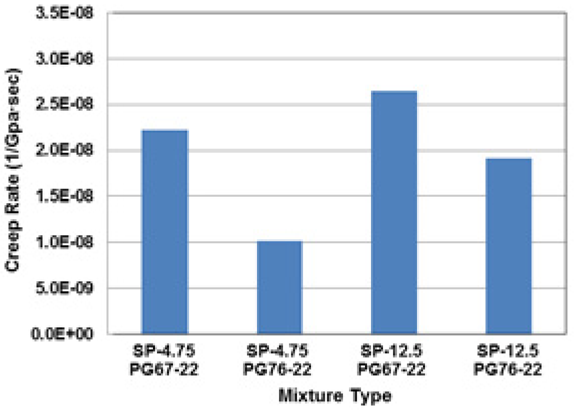
Fig. 6 represents the Superpave IDT test results for each mixture evaluated. Based on the results in Fig. 6, the 4.75 mm mixtures exhibit higher ER value which indicates better cracking resistance than those for 12.5 mm mixtures. In particular, the 4.75 mm mixture with PG 76-22 binder shows significantly higher ER value than the other mixtures. This mixture was capable of maintaining relatively higher $DCSE_f$ which reflects the increased mixture's resistance to damage without a fracture as well as lower creep rate which indicates a decreased rate of damage accumulation for enhanced cracking performance. Also, the mixtures with PG 76-22 binder generally show relatively higher ER values as compared to those with PG 67-22 binder for both 4.75 mm and 12.5 mm mixtures likely due to the effect of polymer modification. Results clearly indicated that the 4.75 mm NMAS mixes have potential benefits on mixture cracking performance. The ER values for 4.75 mm mixtures measured in this study are likely comparable or even higher than those obtained from typical Open-Graded Friction Course (OGFC) and Dense-Graded Friction Course (DGFC) mixtures based on the results of previous research (Li 2009).



(a) Energy Ratio



(b) $DCSE_f$

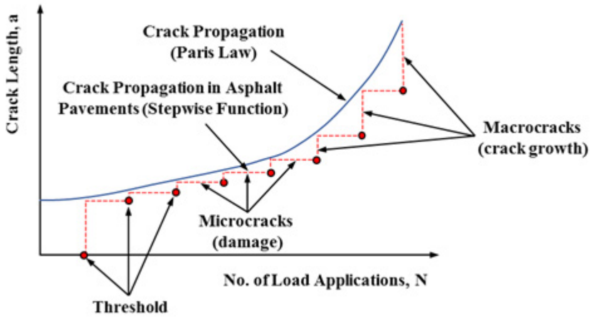


(c) Creep Rate

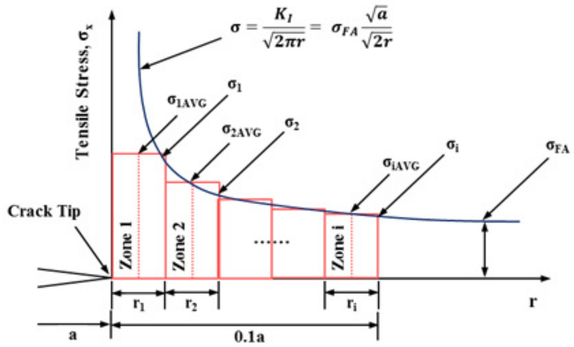
Fig. 6 Mixture Fracture Properties Obtained from Superpave IDT Tests

4.2. Hot-Mix Asphalt Fracture Mechanics (HMA-FM) Model Performance Prediction

Previous research conducted by University of Florida (UF) have developed HMA-FM model and further verified the model based on the crack growth law of asphalt mixtures that is able to fully describe both initiation and propagation of cracks (Roque et al. 2002; Zhang et al. 2001). This model requires the fundamental mixture parameters including fracture thresholds and properties as input values that can be measured using the Superpave IDT tests. For the HMA-FM model, a crack growth law involves the fracture mechanics theory in conjunction with the threshold concept. Fig. 7 illustrates a basic concept of the crack growth law and a stress distribution generalized at near the crack tip subjected to tension, where r = length of process zone, σ_{FA} = far away stress, a = half crack length, and K_I = stress intensity factor. In particular, the HMA-FM defines that stress should be distributed at the crack tip to account for the fact that stress at any part of mixture cannot exceed the maximum limit of mixture, even though traditional linear elastic fracture mechanics assumes the infinite stress at the crack tip (Roque et al. 2002; Zhang et al. 2001). Zhang et al. indicated that in the HMA-FM approach, a stress limit for determination of the stress distribution near the crack tip can be appropriately defined by using tensile strength of asphalt mixtures (Zhang et al. 2001).



(a) Crack Propagation in Asphalt Mixtures



(b) Stress Distribution Near the Crack Tip

Fig. 7 Basic Concepts for the HMA-FM Model (Roque et al. 2002; Zhang et al. 2001)

In Superpave IDT repeated load fracture test mode, a HMA specimen (150 mm diameter and 25 mm thick) with a center hole of 10 mm was subjected to cyclic haversine loads with 0.1 second loading time and 0.9 second resting in each cycle as shown in Fig. 8. It was assumed that the induced tensile stress level (or amplitude of the far field stress σ_{FA}) in the center area of the specimen is 1.0 MPa to estimate the distribution of tensile stress σ_x along the line AB for y axis varied between 5 mm and 30 mm. The tensile stress due to stress concentration along the line AB can be estimated using the following equation, where a_0 = the radius of the center hole (i.e. a_0 = 5 mm), and for $\sigma_{AVG(i,j)}$, i = zone number and j = condition number.

$$\sigma_x = \sigma_{FA}\left(1 + \frac{a_0^2}{2y^2} + \frac{3a_0^4}{2y^4}\right) \tag{1}$$

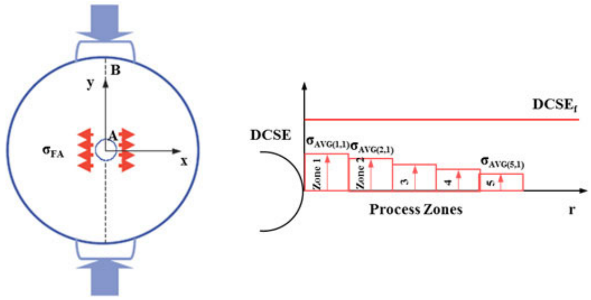
Next, crack initiates after certain amount of load cycles as shown in Fig. 8 (b). The problem now is changed from stress concentration to stress intensity. In this study, the half of crack length was assumed to be 10 mm for estimating the tensile stress distribution along the line AB for axis now varied from 10 mm to 30 mm. The tensile stress due to stress intensity ahead of the crack tip can be estimated using the Eq. (2).

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \tag{2}$$

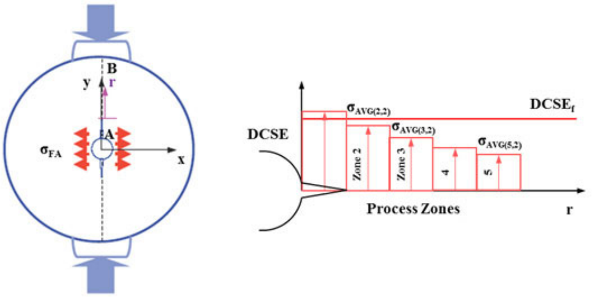
Where, r is a local axis originated at the crack tip and pointing toward point B in Fig. 8 (b), K_I is the tensile mode stress intensity factor that can be approximated as follows where, a is the half crack length (i.e. a = 10 mm) for condition 2 as illustrated in Fig. 8 (b).

$$K_I = 1.12 \cdot \sigma_{FA}\sqrt{\pi \cdot a} \tag{3}$$

In order to predict crack initiation and propagation using HMA-FM model, the fracture properties of four mixtures were used as input values. Table 2 summarizes the fracture threshold and parameters determined for mixtures evaluated.



(a) Condition 1: Before Crack Initiation



(b) Condition 2: After Crack Initiation

Fig. 8 HMA-FM based Approach Using Superpave IDT Repeated Load Fracture Test

Table 2. Input Modulus for HMA-FM Model Prediction

Mixture	m	D_1 (10^{-9}, 1/Pa)	$DCSE_f$ (KJ/m^3)	S_t (MPa)
SP-4.75 PG 67-22	0.49	0.0322	2.89	2.98
SP-4.75 PG 76-22	0.35	0.0557	4.10	2.90
SP-12.5 PG 67-22	0.46	0.0515	2.09	2.44
SP-12.5 PG 76-22	0.41	0.0605	2.55	2.54

Crack initiation and propagation were predicted for each mixture evaluated using HMA-FM model. In this study, a prediction was made with respect to the half crack length "a" versus the increase in the number of load cycles "N" until "a" reaches to 30 mm. Also, a 5 mm of uniform process zone length was assumed for analysis. A total of 5 successive process zones are embedded ahead of the hole as shown in Fig. 8. The DCSE per cycle can be calculated using the following equation where, D_1 and m are mixture properties measured from Superpave IDT creep compliance test given in Table 2. σ_{AVG} is the average tensile stress in any of the process zone. It is noted that each process zone needs to be subdivided in order to obtain σ_{AVG} (i.e. the tensile stress σ_{AVG} can be evaluated at a grid of 0.5 mm along r-axis, then the average stress is calculated within the 5 mm long process zone). Also, the tensile stress σ_r should satisfy $\sigma_{FA} \le \sigma_r \le S_t$.

$$DCSE/cycle = \frac{1}{20}\sigma_{AVG}^2 \cdot D_1 \cdot m(100)^{m-1} \tag{4}$$

Crack initiates when accumulated DCSE exceeds $DCSE_f$ in zone 1 for condition 1 as shown in Fig. 8 and then propagates through zone 1. A number of cycles for crack initiation can be determined as follows.

$$DCSE_f = \left[\frac{DCSE}{Cycle}\right]_{(1.1)} \times N_f(initiation) \tag{5}$$

$$N_f(initiation) = N_{f(1.1)} = \frac{DCSE_f}{\left[\frac{DCSE}{Cycle}\right]_{(1.1)}} \tag{6}$$

When the crack propagated through zone 1 completely, problem changes from stress concentration to stress intensity and new stress distribution needs to be considered and stresses redistribute throughout the remaining zones. A crack propagates when accumulated DCSE exceeds $DCSE_f$ now in zone 2 using the equations below. The same process is continued until all five process zones are cracked.

$$DCSE_f = DCSE_{f(2.1)} + DCSE_{f(2.2)} \tag{7}$$

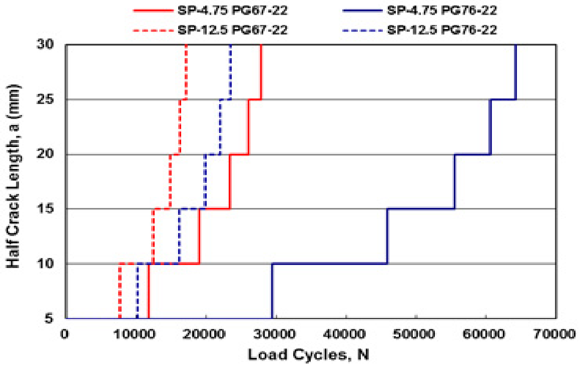
$$DCSE_f = \left[\frac{DCSE}{Cycle}\right]_{(2.1)} \times N_{f(1.1)} + \left[\frac{DCSE}{Cycle}\right]_{(2.2)} \times N_{f(2.2)} \tag{8}$$

$$N_f(propagation) = N_{f(2.2)} = \frac{DCSE_f - \left[\frac{DCSE}{Cycle}\right]_{(2.1)} \times N_{f(1.1)}}{\left[\frac{DCSE}{Cycle}\right]_{(2.2)}} \tag{9}$$

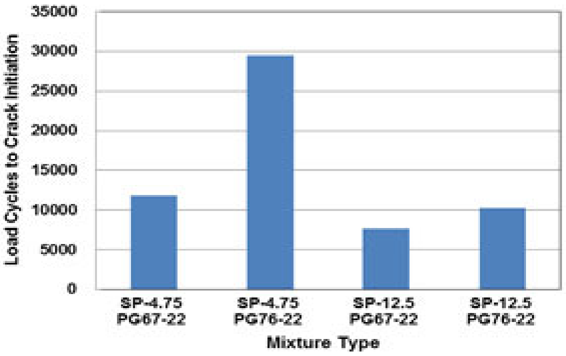
The Eqs. 10 through 12 indicate generalized forms to determine the number of load cycles to failure for the zone i under condition i where, i = 2 through n, and total number of load repetition to fail zone i, $N_{f(i)} = N_{f(i-1)} + N_{f(i,i)}$.

$$N_{f(i,i)} = \frac{DCSE_f - \sum_{k=1}^{i-1} N_{f(k,k)} \cdot \left[\frac{DCSE}{Cycle}\right]_{(i,k)}}{\left[\frac{DCSE}{Cycle}\right]_{(i,i)}} \tag{10}$$

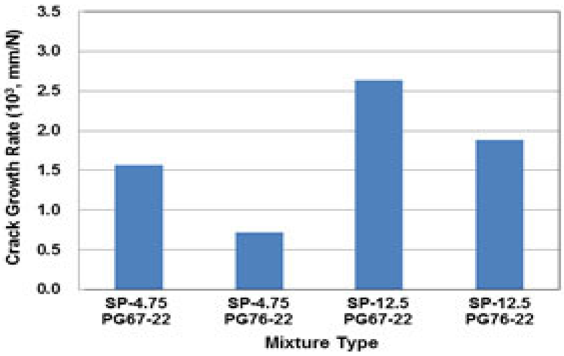
Fig. 9 represents the prediction results of crack initiation and propagation for four mixtures evaluated using HMA-FM model until the half crack length reached 30 mm. The number of cycles to crack initiation as well as the crack growth rate was determined based on the results analyzed. Overall, the 4.75 mm mixtures show relatively better cracking performance than 12.5 mm mixtures regardless of asphalt binder types as indicated by both greater number of load cycles to crack initiation and lower crack growth rate predicted. In particular, the 4.75 mm mixture with PG 76-22 binder shows superior cracking resistance than other mixtures evaluated. Also, it is interesting to remark that the cracking performance predicted using the HMA-FM model matched well with those indicated by the ER results as shown in Fig. 10.



(a) Load Cycles vs. Half Crack Length

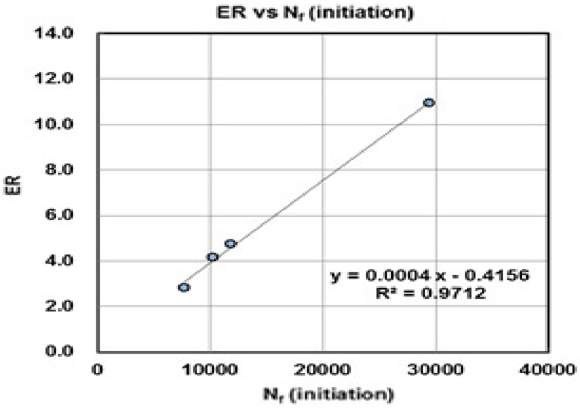


(b) Number of Load Cycles to Crack Initiation

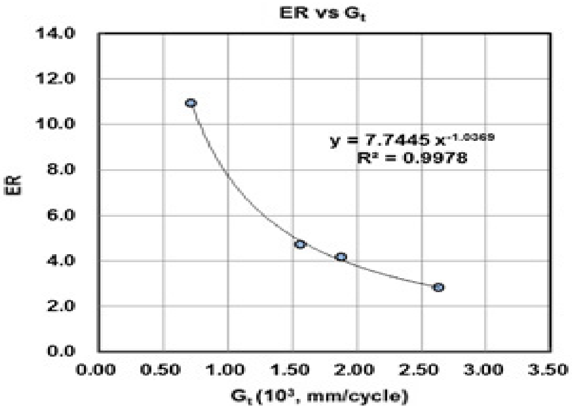


(c) Crack Growth Rate

Fig. 9 HMA-FM Model Performance Prediction Results



(a) ER vs. Number of Cycles to Crack Initiation



(b) ER vs. Crack Growth Rate

Fig. 10 Relationship between ER and HMA-FM Model Prediction Results

5. CONCLUSION

The performance characterization of 4.75 mm NMAS asphalt mixtures for both rutting and cracking was conducted using full-scale field experiments and laboratory-scale mixture tests, respectively. A summary of findings and conclusions is presented as follows.

1. Based on the results of APT rut evaluation, rutting performance is likely not as good for pavements with 4.75 mm mixtures as a surface course compared to those for pavements with typical 12.5 mm mixtures.
2. It was found that the effect of 4.75 mm layer thickness is more significant than that of asphalt binder type on rutting performance of pavement structure with relatively thin application of 4.75 mm NMAS asphalt mixtures.
3. It is clearly indicated that a primary source of rutting is confined within a layer of 4.75 mm mixture due to relatively higher mixture instability, lower aggregate

interlocking effect, and decreased shear resistance that result in a greater rutting potential of 4.75 mm mixtures than 12.5 mm NMAS asphalt mixtures.

4. The ER values of 4.75 mm mixtures obtained using Superpave IDT tests are likely comparable or even higher than those measured from typical OGFC and DGFC mixtures which reflect the potential benefits of 4.75 mm mixes on mixture cracking resistance.
5. The decreased crack growth rate as well as the increased number of load cycles to crack initiation for 4.75 mm mixtures predicted by the HMA-FM based model manifested the better cracking performance of the 4.75 mm mixtures than 12.5 mm mixtures.
6. It is recommended that adequate thickness and binder type be considered for proper application of 4.75 mm mixture as a surface course of layered flexible pavement system to effectively resist rutting and cracking.
7. As far as implementation, the best use of 4.75 mm NMAS mixtures appear to be as a surface course for low traffic volume applications and these mixes can be properly used as a preservation treatment and does not have to last as long as typical 12.5 mm NMAS mixes.

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