Time-Dependent Stiffness Increase of Foamed Asphalt Stabilized Base Material

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ABSTRACT: Foamed asphalt stabilized base (FASB) is a cold-recycling process that combines reclaimed asphalt pavement and/or recycled concrete with a small amount of foamed asphalt binder. The combination of water and binder causes a gain in stiffness after placement due to drying effects and the irreversible bonds formed between the binder and aggregate during curing. To investigate this process, a series of experiments was conducted on a 20 cm thick FASB base layer for a lane addition project in Maryland. In-place overall stiffness of the section was measured over seven consecutive days using a Zorn lightweight deflectometer (LWD) and a Humboldt GeoGauge. The stiffness increase with time was compared to that for a conventional 20 cm thick granular aggregate base (GAB) on top of the same subgrade. The stiffness values measured by each of these in-situ devices were different because of differences in applied stress states and zones of influence and the influence of subgrade stiffness on the overall response. The stiffness increases for both the FASB and GAB layers were corrected based on elastic 2-layer assumptions which revealed that the equivalent stiffness of FASB layer increases by a modulus ratio (F_U) of 8.2 while this factor is about 3.9 for the GAB layer. F_U was predicted using partially saturated soil mechanics, which affirmed that the stiffness gain in FASB layer is significantly higher than can be explained by mere drying of granular materials. This higher rate of stiffening in FASB layer reveals the effects of curing and the development of adhesive bonds between the binder and coated aggregates. The long-term post-construction stiffness was also measured using a Dynatest falling weight deflectometer (FWD) on the final pavement structure 4 months after construction. Backcalculated layer moduli showed that the final stiffness of the field-cured FASB was about 2524 MPa, 15 times higher than that for the GAB material.

KEY WORDS: Foamed asphalt, cold-recycling, unsaturated soil mechanics, curing versus drying, in-situ stiffness.

1 INTRODUCTION

Foamed asphalt stabilized base (FASB) provides a cost-effective and environmentally friendly pavement rehabilitation strategy. To produce FASB, foamed asphalt, which is hot bitumen mixed with a controlled flow of cold water and pressurized air, is blended together with aggregates, e.g. recycled asphalt pavement (RAP) and/or recycled Portland cement concrete (RC) at ambient temperature (Csanyi, 1957; Bowering, 1970; Wirtgen, 2010). The product is a partially bound material consisting of aggregate skeleton, mineral phase, and foamed asphalt mastic. The blend of foamed asphalt and fine aggregates, water, and air voids produces a material with distinct behavior that lies between that of hot mix asphalt (HMA) and granular aggregate base (GAB).

FASB materials gain stiffness in the field with time. This gain in stiffness forms in the mineral phase (similar to any granular material) and the foamed asphalt mastic phase. In other words, the two following processes occur in parallel:

1. Drying of the mineral phase: The mineral phase gets stiffer as water evaporates and matric suction increases (Fredlund and Rahardjo, 1993). This drying-induced stiffening occurs in any granular material and is mostly reversed when water is reintroduced into the material.

2. Curing of the foamed asphalt bonds: Hardening of the asphalt mastic and discrete adhesive bonds develop between the foamed asphalt mastic droplets and the larger aggregates. Bowering (1970) found that curing of FASB occurs simultaneously with moisture evaporation from the mixture. Fu et al. (2010) studied different curing strategies in the lab and found that curing of FASB is hampered if the mixing/compaction water is retained in the material after compaction. However, once these bonds are formed, they are only moderately sensitive to moisture damage as compared to the drying-induced bonds in the mineral phase. The tensile strength ratio (TSR) test confirms that foamed asphalt bonds are largely irreversible (Khosravifar et al., 2012, Fu et al., 2010).

To further investigate this time-dependent drying and curing process, the stiffness of a 20 cm thick FASB layer placed on top of a subgrade was monitored in the field over consecutive days after placement using a Humboldt GeoGauge 4140 and Zorn ZFG 3000 LWD and at several months later after HMA paving using a Dynatest FWD. The stiffness gain of the FASB sections were compared to that in a companion GAB section. Both the GAB and FASB sections were placed in July 2011 under similar climatic condition with a mean daily temperature of 26°C and a relative humidity of 67%.

The test sections discussed in this work were part of a comprehensive case study on FASB material and were referred to as 'FASB Segment-B' and 'GAB' sections in the work by Khosravifar et al. (2013b). In this paper, however, only the 'FASB Segment-B' section is considered and termed the FASB section for conciseness. The other FASB sections in the overall study were placed under different climatic conditions and/or with different construction techniques and were therefore excluded from the present discussion.

In addition to the field observations, the stiffness increases for both the FASB and GAB material due to drying were interpreted using partially saturated soil mechanics models, namely: (a) the one-dimensional enhanced integrated climatic model (ARA, 2004) which is currently incorporated in the new Mechanistic–Empirical Pavement Design Guide (MEPDG) to assess the changes in the modulus of unbound material due to the changes in their moisture content, and (b) a revised model presented by Cary and Zapata (2010), referred to herein as the PC Enhanced model. The predictions were compared to the field observations.

2 MATERIAL PROPERTIES AND TESTING PROCEDURE

The FASB mixture evaluated in this study consisted of 40% RAP and 60% RC blended with 2.8% foamed asphalt at ambient temperature. The PG 64-22 binder used in the mix was foamed with 2.2% foaming water content at 160ºC. The detailed information about the material characteristics and the mix design is provided under "Mix Group A" in Khosravifar et al. (2012).

Figure 1.a shows the grain size distribution of the GAB and FASB material according to AASHTO T 27. The soil water characteristic curves (SWCC) of the materials were predicted based on their grain size distribution and index properties using the methodology presented by Perera et al. (2005) and are presented in Figure 1.b.

The 20 cm thick FASB and GAB layers were placed in July 2011 in two 10 cm thick lifts and were compacted to the target modified Proctor maximum dry density of 1960 kg/m^3 and 2384 kg/m^3, respectively. Table 1 summarizes some of the material properties for the FASB and GAB materials immediately after compaction.

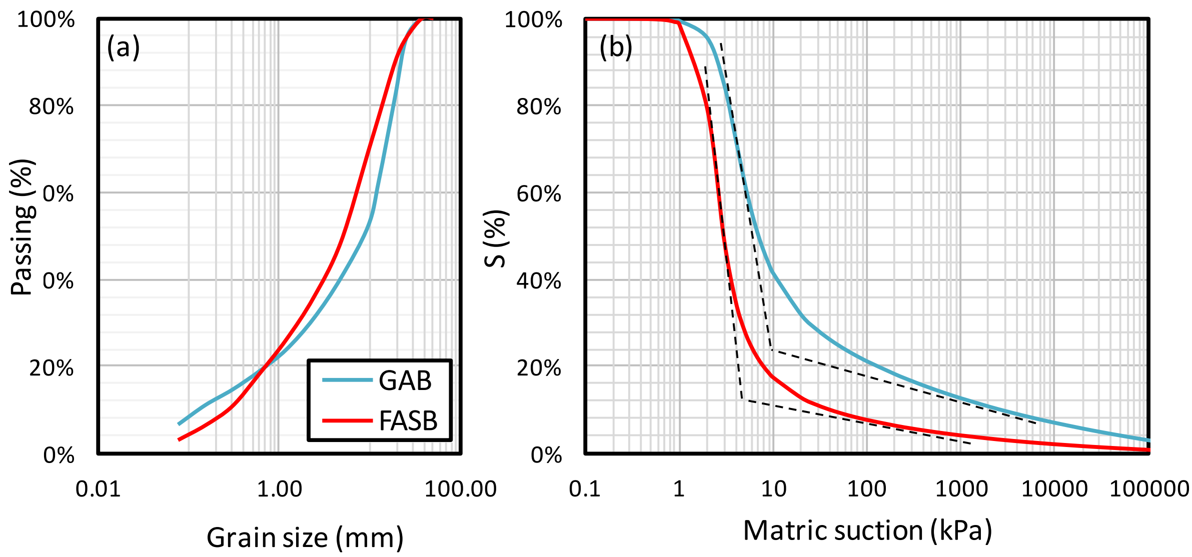

Figure 1: FASB and GAB material properties: (a) grain size distribution, and (b) soil water characteristic curves (SWCC).

Table 1: GAB and FASB properties after compaction.

Material	Percentage passing sieve #200 (%)	Moisture content (%)	Dry density (kg/m3)	Maximum Specific Gravity	Degree of Saturation (%)
	AASHTO T 27	AASHTO T 180- method D, AASHTO T 224			
GAB	6.7	5.2	1960	2.77	55
FASB	3.1	10.2	2384	2.44	64

The average temperature at placement was 26°C at a relative humidity of 67%. Precipitation was negligible during the study. The materials were placed and compacted using a Bomag intelligent compactor to achieve 100% of maximum modified Proctor dry density (AASHTO T 180- method D). Details on the field construction operations are documented in detail in Khosravifar et al. (2013b).

The increase in in-situ stiffness with time was measured using the GeoGauge 4140 and the Zorn ZFG 3000 LWD devices during the first week after FASB placement. The measurements on the GAB section were performed on the day of its placement and the following day. Subsequent measurements were interrupted on the GAB section. However, its potential equilibrium stiffness in the field was obtained on an undercut section filled with GAB material. Although this stiffness measurement is not exact, the authors believed it provided a good estimate of the equilibrium modulus expected from GAB in the field.

The GeoGauge and Zorn LWD in-situ test devices apply a load and measure the surface deflection. The surface deflection is a composite response of the material in the zone of influence of the test device and is influenced by the relative stiffness of the layers. Other factors influencing the measurements are the frequency of applied load and the induced stress states. Most important, the stiffness reported by the devices is based on elastic homogeneous isotropic semi-infinite half-space assumptions, and therefore is an overall stiffness of the material in the device's zone of influence. This will in general differ from the true equivalent stiffness of FASB or GAB layer. These overall stiffness values reported directly from the test devices are referred to in the text as the stiffness of the FASB or GAB "section" as opposed to FASB or GAB "layer".

The GeoGauge user manual (Humboldt, 2007) reports the depth of the zone of influence to be 20 to 30 cm. The zone of influence of the Zorn LWD was estimated to be deeper than the GeoGauge, at about twice the diameter of the loading plate or about 60 cm.

Khosravifar et al. (2013b) found that the Zorn LWD underpredicted the stiffness by a factor of 0.5 compared to the GeoGauge because of the aforementioned factors. Moreover, it was concluded that the practical upper stiffness measurement limit of the GeoGauge and Zorn LWD to be about 450 MPa and 210 MPa, respectively.

3 PREDICTIONS BASED ON UNSATURATED SOIL MECHANICS MODEL

3.1 MEPDG model

The new Mechanistic–Empirical Pavement Design Guide (MEPDG) uses a one-dimensional Enhanced Integrated Climatic Model (ARA, 2004) to assess the changes in moisture content in the soil over time and depth. The empirical Equation 1 developed by Witczak et al. (2000) quantifies the corresponding stiffness changes in the unbound materials:

$$LogF_U = a + \frac{b-a}{1+e^{\left(ln\frac{-b}{a}+k_m\times\left(S-S_{opt}\right)\right)}} \qquad (1)$$

in which $F_U = E/E_i$, which is the ratio of modulus at a given time to the modulus at its optimum conditions (E_i); a = minimum of log F_U (−0.3123 for coarse grained materials); b = maximum of log F_U (0.3010 for coarse grained materials); k_m = regression parameter (6.8157 for coarse grained materials); and $S - S_{\text{opt}}$ = variation in the degree of saturation S (decimal) with respect to the degree of saturation under optimum conditions (S_{opt}). This model was used to predict the maximum and likely modulus ratios (F_U) of the material, which correspond to dry and expected residual moisture conditions, respectively.

Residual saturation level is determined as the saturation level where a large suction change is required to remove additional moisture from the soil (Fredlund and Xing, 1994). The residual saturation level of 12% and 24% were obtained from the SWCCs (Figure 1.b) for FASB and GAB materials respectively, based on the methodology presented in the work by Fredlund and Xing (1994).

Dry conditions at near zero moisture content are unlikely to happen in the field because of soil resistance to moisture loss. However, the dry condition represents the upper bound for stiffness gain due to the drying effect. The predicted values from the MEPDG model are summarized in Table 2 for the FASB and GAB materials.

The MEPDG model assumes a maximum modulus ratio (F_U) of 2 as the upper limit for coarse grained materials (b=0.3010). This was found to be fairly accurate according to Cary and Zapata (2010). However, they also concluded that F_U for course grained materials is influenced by the degree of compaction, which was the basis for their enhanced model.

3.2 PC Enhanced model

The model presented by Cary and Zapata (2010) is a revised version on the previous EICM model in the MEPDG which accounts for the effects of compaction energy on the moisture susceptibility of coarse grained material. The enhanced model at the reference condition of 100% standard Proctor compaction energy is expressed as:

$$F_{U-PC} = 10^{\left(-0.40535+\frac{1.20693}{1+e^{\left(0.68184+1.33194\times\left(\frac{S-S_{opt}}{100}\right)\right)}}\right)} \times 10^{0.03223(PC-100)} \tag{2}$$

PC is defined as the percentage of standard dry density and was assumed to be 105%. Note that the FASB and GAB layers in the study were compacted to the target maximum dry density as measured by the modified Proctor compaction test (AASHTO T 180).

The PC Enhanced model by Cary and Zapata predicted higher modulus ratios for the dry and expected residual moisture condition as compared to the MEPDG model. The results are summarized in Table 2.

Table 2: Predicted F_U with the partially saturated soil mechanics models.

Material	GAB			FASB		
S (%)	55	12	0	64	24	0
Moisture status	Optimum	Residual	Dry	Optimum	Residual	Dry
F_U MEPDG model	1	1.7	1.9	1	1.8	2.0
F_U-PC Enhanced model	1	1.9	2.4	1	2.3	2.6

4 FIELD TEST RESULTS AND COMPARISON TO THE PARTIALLY UNSATURATED MODELS

Figure 2 shows the increase in the overall in-situ stiffness over time for the GAB versus the FASB section as measured by the Zorn LWD and the GeoGauge. The average initial stiffness (E_i) of the FASB section was 75 MPa, while it was about half that value (39 MPa) for the GAB section based on the measurement using the Zorn LWD. The GeoGauge provided higher moduli as compared to the Zorn LWD. Nevertheless, the FASB was stiffer than the GAB (146 MPa versus 108 MPa).

The overall stiffness of the FASB section increased to an average value of 245 and 452 MPa at 3 days after placement, as measured by the Zorn LWD and the GeoGauge, respectively. In contrast, the final stiffness of the GAB section at its equilibrium moisture content was only about 111 to 226 MPa as measured by the Zorn LWD and the GeoGauge, respectively. The FASB section started at a higher stiffness, gained stiffness at a higher rate, and equilibrated at 2.1 to 2.3 times the stiffness of the GAB section after one week of field curing and drying.

Both the Zorn LWD and GeoGauge stiffness measurements on the FASB section exhibited higher variability as the material stiffened and the devices approached their measurement limits after 3 to 4 days of field drying and curing. This is reflected in the larger size of the error bars of Figure 2 for the 7th day measurements on the FASB sections.

In order to better compare the stiffness increases in the GAB and FASB sections, the normalized F_U ratios were plotted in Figure 3. These measured ratios were compared to the predicted maximum ratios by the MEPDG and the PC Enhanced models, which are also included in Figure 3. The vertical columns show the models' maximum predicted values for the FASB material. The small horizontal lines on the prediction bars demonstrate the residual and maximum F_U values for the GAB and the FASB as tabulated in Table 2.

Just two days after placement of the FASB material, the overall stiffness of the section exceeded the highest predicted F_U from the two models, which are based only on the drying effects on modulus. On the other hand, the stiffness of the GAB section was better predicted by the models, especially considering that the final (nth day) measurements for the GAB sections were at a different spatial location. The Zorn LWD and the GeoGauge F_U values of 2.1 to 2.9 on the GAB section are close to the values predicted by the MEPDG and the PC Enhanced models. The higher F_U values of 3.2 to 3.3 for the FASB section suggest that some of the stiffness increase observed in the FASB sections is due to curing rather than the mere drying of the material.

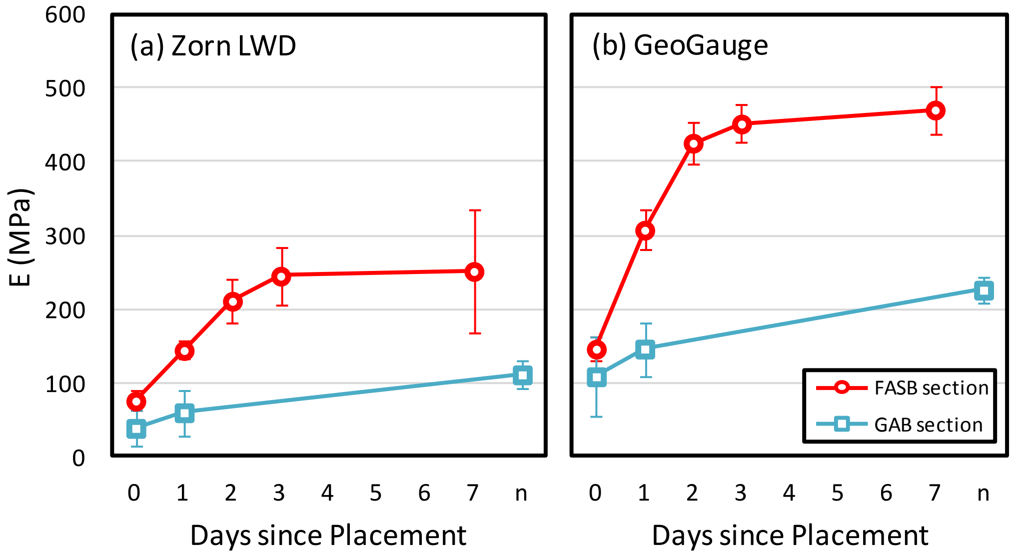

Figure 2: The average overall stiffness of FASB and GAB sections with time as measured using (a) the Zorn LWD, and (b) the GeoGauge; error bars represent one standard deviation.

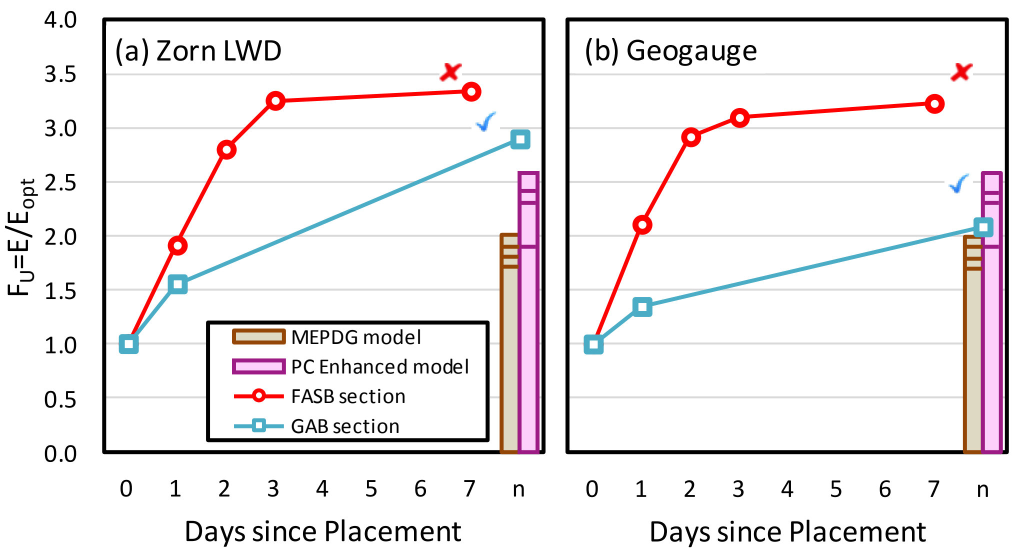

Figure 3: F_U for FASB and GAB sections versus time as measured using (a) the Zorn LWD and (b) the GeoGauge versus the maximum modulus ratio predicted by the MEPDG and the PC Enhanced models.

It is important to note that the F_U ratios are based on the overall stiffness of the test section and not just the properties of the FASB or the GAB layer. Khosravifar et al. (2013a) studied the influence of subgrade stiffness on the overall modulus reported by LWD for a 20 cm thick base layer via a finite element analysis assuming the system as a 2-layer elastic homogeneous isotropic semi-infinite half-space with Poisson's ratio of 0.35. Figure 4 summarizes the amount of under/over prediction of LWD due to subgrade moduli effects. It can be inferred from the figure that high relative errors may occur if the modulus of the layer of interest is far from that of the underlying layer. The LWD provides near-perfect measurements if the ratio of the E_{LWD}/E_{SG} is close to 1, and thus in better agreement with the single-layer elastic homogeneous isotropic semi-infinite half-space assumptions.

The equivalent stiffnesses of the 20 cm FASB and GAB layers were calculated based on the LWD measurements as corrected using Figure 4. An average subgrade stiffness of 136 MPa was used to normalize the LWD measurements. This subgrade modulus was measured using the Zorn LWD in May 2011. The subgrade stiffness measurements were not performed on the same locations as the FASB or GAB tests. However, the measurements on the subgrade were performed on the same material in the site under fairly similar climatic conditions with average air temperature and relative humidity of 26°C and 69%.

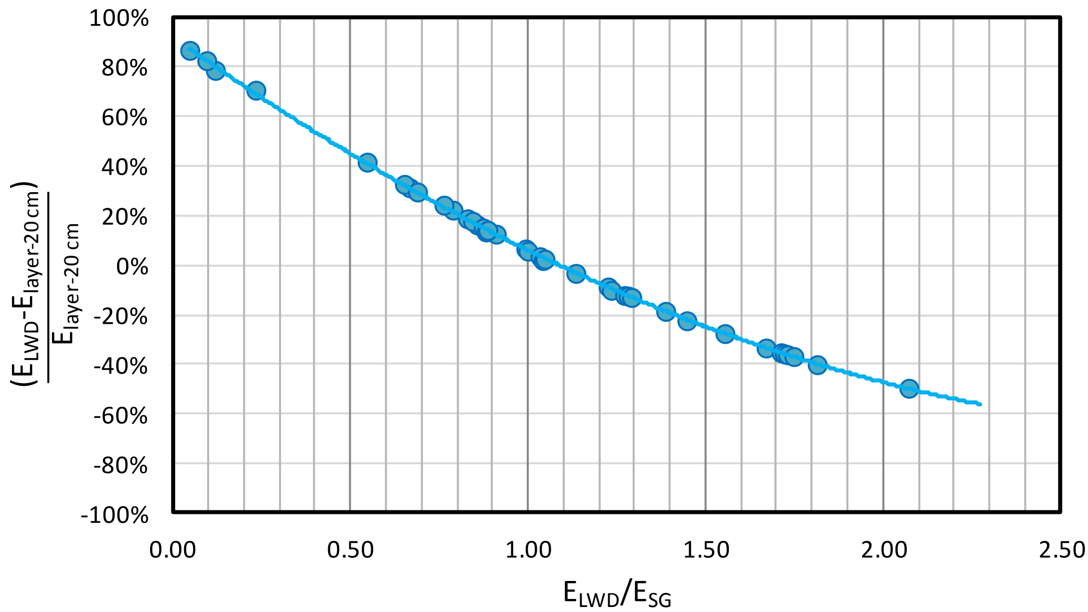

Figure 4: Relative error in LWD measurements ($\frac{E_{LWD}-E_{layer\text{-}20\ cm}}{E_{layer\text{-}20\ cm}}$) versus E_{LWD}/E_{SG}. Poisson's ratio = 0.35. After Khosravifar et al., 2013a.

Figure 5.a demonstrates the corrected stiffnesses of the FASB and GAB layers versus the overall reported stiffness from the Zorn LWD. The plot shows that the stiffness of the FASB layer may have been significantly underestimated by the LWD; after two days of curing the relative errors are as high as -44%. On the other hand, the stiffness of the GAB layer was slightly overestimated by the LWD.

The measured increase in modulus ratio of the FASB layer was significantly higher than that measured in the GAB layer and the predictions from both models as shown in Figure 5.b. The F_U of 8.2 for the FASB after one week of placement clearly supports the hypothesis that curing of the foamed asphalt bonds is the most significant component in the stiffening of FASB.

Since both the Zorn LWD and GeoGauge approached their measurement limits on or after the 4th day measurements on the FASB sections, it is not clear whether the stiffness of the FASB material stabilized and reached equilibrium or the curing was still ongoing. To better investigate the ultimate stiffness of the materials, Dynatest falling weight deflectometer (FWD) measurements were performed on the paved sections four months after construction, immediately before opening the site to traffic on November 2011.

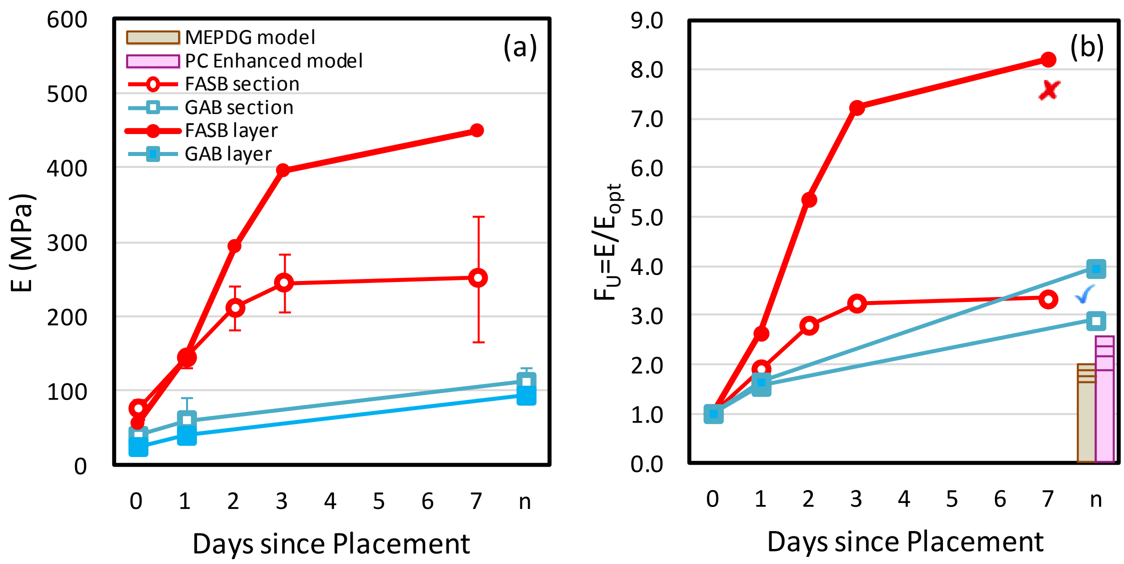

Figure 5: (a) Stiffness of FASB and GAB layer moduli assuming the pavement structure as a two-layer system; (b) F_U as measured for the overall sections, individual FASB and GAB layers, and as predicted by the MEPDG and PC Enhanced models.

The backcalculation analysis was performed using ModTag V 4.3.0. The results are plotted in Figure 6 for the (a) HMA, (b) base and (c) subgrade of the FASB and GAB sections. The RMS errors were less than 6.7% with an average of 3.4%, indicating good backcalculation results. The backcalculated subgrade modulus was 299 MPa on average and relatively constant, being only slightly stiffer under the FASB section. The modulus of the FASB layer was about 2524 MPa, more than 15 times greater than the 166 MPa modulus backcalculated for the GAB.

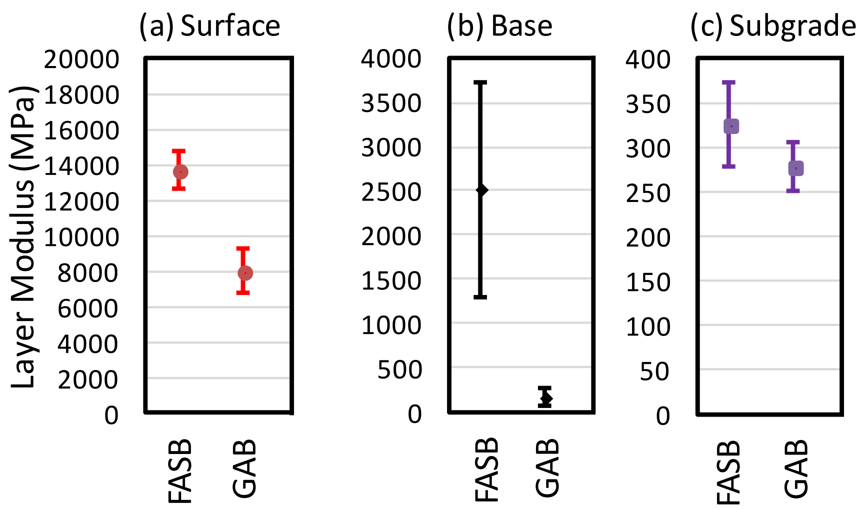

Figure 6: Backcalculated moduli for (a) HMA surface layer, (b) base layer, and (c) subgrade. Error bars indicate one standard deviation.

Other evidence of the curing vs. time behavior of the FASB material was observed during attempts to obtain cores from the field cured material. While it was impossible to obtain intact cores from the FASB material after 7 days of curing, intact cores could be obtained from the FASB material after 4 months of curing, demonstrating that curing continued for considerable time after initial placement.

5 CONCLUSIONS

Foamed asphalt stabilized base (FASB) is a cold-recycling process that combines reclaimed asphalt pavement and/or recycled concrete with a small amount of foamed asphalt binder. The combination of water and binder causes a gain in stiffness after placement due to the drying effects and the irreversible bonds formed between the binder and aggregate during curing.

To investigate this process, stiffening of a 20 cm thick FASB base layer was monitored and compared to that of a companion GAB layer. In-place overall stiffness of the section as measured by a Zorn LWD and a GeoGauge device showed a higher stiffness and rate of stiffening for the FASB section.

The stiffness values measured by each of these in-situ devices were different because of differences in applied stress state, zones of influence, and the influence of the subgrade stiffness on the overall response. The stiffness measurements by the Zorn LWD were corrected based on 2-layer elastic assumptions from a study by Khosravifar et al. (2013a). Comparisons of the stiffness of the FASB and GAB layers versus the overall stiffness of the section measured by the Zorn LWD showed that the stiffness of the FASB layer was significantly underestimated by the LWD readings, particularly after two days of curing. Relative errors in LWD readings were as high as -44% for the FASB layer. On the other hand, the stiffness of the GAB layer was slightly overestimated by the LWD.

In addition to the field observations, the stiffness increase for both the FASB and the GAB materials due to drying effects were interpreted using two partially saturated soil mechanics models: (a) the EICM model currently used in the MEPDG (ARA, 2004), and (b) a revised model presented by Cary and Zapata (2010) referred to herein as the PC Enhanced model. Both models define moisture-related modulus changes in terms of F_U, defined as the ratio of the modulus at a given saturation level to the modulus at the saturation level corresponding to the optimum moisture content. The MEPDG model suggested a maximum F_U of 2.0 for an upper bound condition of complete drying for the coarse grained material. The PC Enhanced model predicted a slightly higher maximum F_U of 2.4 to 2.6. The potential F_U factors associated with more realistic equilibrium moisture conditions expected in the field were slightly lower than the upper bounds, and ranged from 1.7 to 1.9 for the GAB, and 1.8 to 2.3 for FASB, based on the two models.

The modulus ratios obtained from the LWD measurements suggested an F_U factor of 8.2 for the FASB layer as compared to the lower factor of 3.9 for the GAB layer at one week after placement.

Both models closely but slightly under predicted the measured stiffness gain for the GAB layer, with PC Enhanced model providing relatively better predictions. The slight underprediction in the models could be due to inaccuracies in the field measurements, potentially higher field compaction energies, or model errors. The PC Enhanced model provided a better prediction of GAB stiffness by incorporating the effect of compaction energy.

The under-prediction of the FASB stiffness gain by both models was significant. This strongly supports the conclusion that the stiffness gain in the FASB layer is significantly higher than what can be explained by mere drying. This higher rate of stiffening in the FASB layer confirms the beneficial effects of field curing and the development of adhesive bonds between the binder and coated aggregates.

Long-term stiffnesses were also measured using a Dynatest FWD on the final pavement structure 4 months after construction. Backcalculated layer moduli indicated that the final stiffness of the field-cured FASB was about 2524 MPa, 15 times higher than that of the GAB material.

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