

# Stiffness Evolution of Granular Materials Stabilized with Foamed Bitumen and Cement

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From the literature, it is possible to find two trends regarding the stiffness evolution of foamed bitumen stabilized–recycled mixtures. The first trend indicates that once the foamed bitumen mix reaches a constant value because of the curing process, the stiffness decreases with time because of load cycles. The second trend indicates that stiffness remains constant after the curing process. In this research, the stiffness evolution of foamed bitumen mixes stabilized with different bitumen and cement contents was studied. The stiffness was measured by using the indirect tensile fatigue test. Results indicated that once the foamed bitumen mix reached a constant value because of the curing process, stiffness decreased or remained constant depending on the stress level applied to the foamed bitumen layer. If the stress level is lower than a specific value, the stiffness of the mix will remain constant at a value extremely close to the initial stiffness. If the stress level is greater than a specific value, the stiffness of the mix will decrease gradually. In addition, the reduction rate of the stiffness will be greater with higher stress level. The analysis of results from mixes with different bitumen and cement contents allows identification of the effect of both stabilizing agents in the long-term stiffness evolution.

Stabilizing or recycling of asphalt concrete pavements by using foamed bitumen (FB) is a widely used rehabilitation technique worldwide. However, uncertainty still exists when a pavement structural analysis is performed, and a specific design methodology has yet to be fully validated by practitioners and researchers. One main reason for this lack of validation lies in the fact that the elastic modulus that the FB-stabilized layer develops with time is difficult to predict. Although several laboratory tests are available for assessing the stiffness of FB mixtures, no common methodology is available to measure stiffness evolution with time as it relates to changes that have been observed in the field.

Two trends are found in the literature regarding the in situ stiffness evolution of an FB mix. The first comes from studies by Loizos, who analyzed backcalculated stiffness from falling weight deflectometer (FWD) tests from an FB recycling project in Greece (Figure 1) (1). Results indicated that stiffness gradually increased from the day of

construction until it reached a constant value after approximately 12 months. An explanation for this behavior is the loss of moisture from the mixture that occurs during the curing period. The loss of moisture and increase in strength or stiffness has also been observed by Bowering (2), Jones et al. (3), and Fu et al. (4), among others. In the research work of Loizos, the backcalculated stiffness remained constant after 12 months despite constant traffic of heavy vehicles (1).

Conversely, research studies in South Africa (5) indicated that FB layers exposed to traffic load showed a gradual decrease in stiffness. Figure 2 shows results of accelerated pavement testing performed on a recycled pavement with an FB layer with 1.8% bitumen and 2.0% cement content. After pavement construction, a 40-kN traffic load was applied with the South African heavy vehicle simulator (6, 7). Multidepth deflectometers were installed in the pavement structure to measure deflection and to calculate the effective stiffness of each layer.

Stiffness values measured during the period of analysis indicated that the FB layer had two phases. The first one corresponded to a decrease in stiffness until a constant stiffness state, without having a physical manifestation on the pavement layer (cracks or deformations). The second one was represented by a constant stiffness of the FB layer. During the test at approximately 1 million load cycles, the traffic was increased to 80 kN. With the 80-kN load, the stiffness of the FB layer showed a similar trend to that observed during the first 300,000 load cycles with 40 kN, with stiffness decreasing gradually until plateaus were reached. Results provided by the accelerated pavement test in the long term also indicated that during the second phase the material behaved as a granular material, accumulating permanent deformation from the application of the cyclic loads. The TG2 guide of 2002 proposed that the “constant stiffness state” should be comparable to that of a granular material only in the effective elastic modulus and behavior but not in physical composition of the materials (8).

## INFLUENCE OF ACTIVE FILLER ON MECHANICAL PROPERTIES OF FB MIXES

Active fillers are normally added to an FB mix to improve the mechanical properties of the mixture. While some researchers and practitioners have reported mixes without any active filler (4, 9), others have reported the use of cement (10–13), lime (14–16), fly ash (17, 18), and other types of active fillers (18–20). Nevertheless, recent studies have demonstrated that stiffness of FB mixtures is dependent on both the type of active filler and the content. Halles and Thenoux reported differences of up to two times between mixes with

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*Transportation Research Record: Journal of the Transportation Research Board*, No. 2363, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 105–112.  
DOI: 10.3141/2363-12

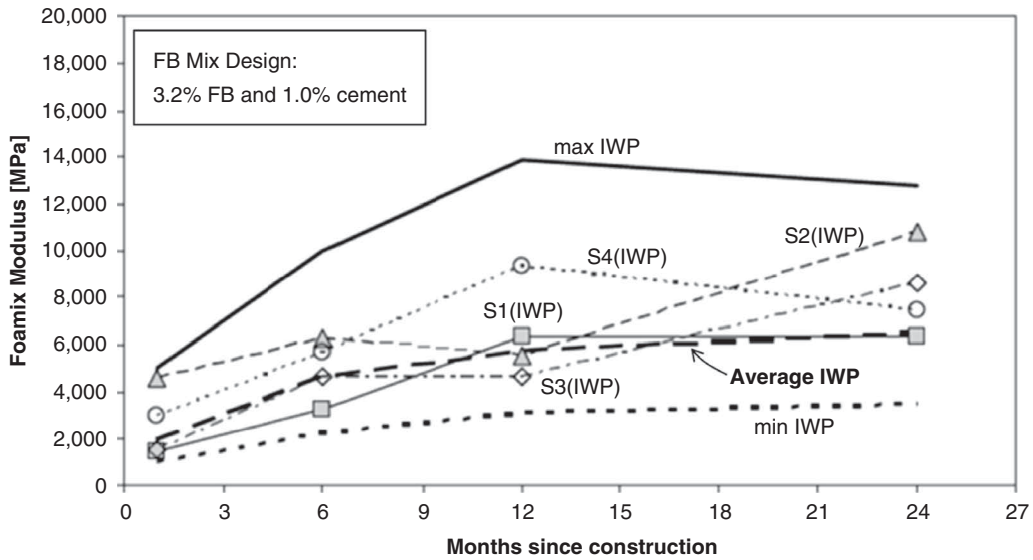


FIGURE 1 Elastic modulus backcalculated by Loizos for FB layer (1) (max = maximum; S = stations; IWP = points between traffic wheel path; min = minimum).

and without cement, for the same FB content, measured by using the repeated-load triaxial test (18). The use of lime also significantly improved the resilient modulus measured in the triaxial test (by a transmission X-ray microscope) of the FB mix. Hence, in addition to determination of the test that better characterizes the mechanical properties of the FB mixture, evaluation of the relative contribution of the active filler used is also recommended, in particular the type and percentage of filler added to the FB mix.

**ANALYSIS OF IN SITU STIFFNESS OF FB MIXTURES**

Stiffness evolution observed in pavement structures by using FB layers can be explained by studying the microstructure of the FB mixture. The tiny bitumen particles as well as the active filler

disperse through the aggregate by adhering to the finer particles (fine sand and smaller), forming a mastic that bonds large aggregates. The bonds formed by the stabilizing agents (bitumen and active filler) are not continuous throughout the microstructure of the aggregates matrix because of the relatively small proportion of both materials; the physical bond may be described as “spot welded” (21). When traffic loads are applied to the pavement structure, the FB layer is deformed and produces strains and stresses in the microstructure. These stresses could break some of the bonds depending on the magnitude of the stresses, orientation, and concentration and produce a decrease in cohesion and therefore a decrease in stiffness. If stresses or strains are smaller than the limiting stress of the mastic, then the FB mix will maintain its original cohesion and therefore its stiffness.

It is well known that FB mixes can bear tensile stress, but like many other materials, they may have a relatively short fatigue life

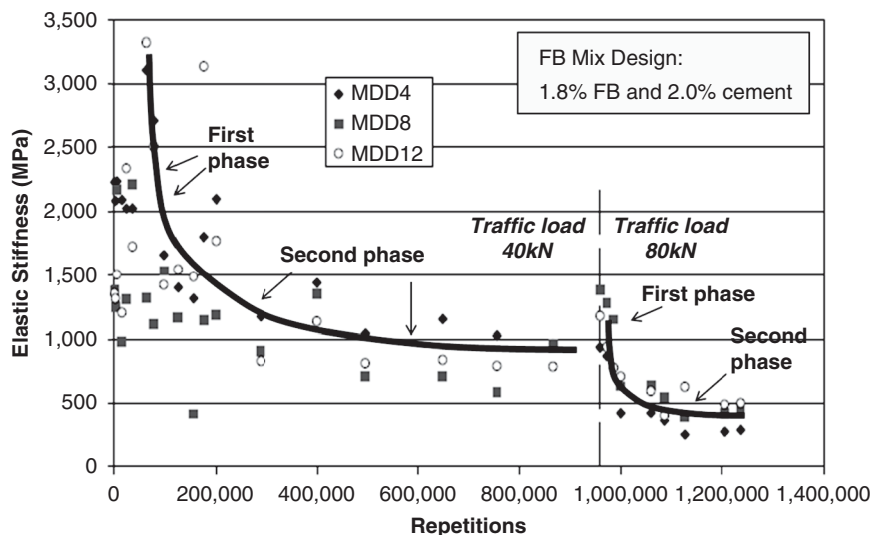


FIGURE 2 Evolution of FB layer stiffness.

**TABLE 1** Characteristics of Pavement Structure and Stresses–Strains Found in Projects from Greece and South Africa

Layer	Elastic Modulus (MPa)	Greece				South Africa			
		T (cm)	$\sigma$ (kPa)	$\epsilon$ ( $\mu\text{m}$ )	SR	T (cm)	$\sigma$ (kPa)	$\epsilon$ ( $\mu\text{m}$ )	SR
Surface	4,000	9	NA	NA	NA	3	NA	NA	3
FB	1,200	25	60	45	0.2	25	165	100	0.55
Other	1,000 <sup>a</sup>	10	NA	NA	NA	NA	NA	NA	NA
Subbase	250	15	NA	NA	NA	25	NA	NA	25
Subgrade	90 <sup>b</sup>	NA	NA	NA	NA	NA	NA	NA	NA

NOTE: T = thickness of layer;  $\sigma$  = stress;  $\epsilon$  = strain; SR = stress divided by indirect tensile strength; NA = not available.

<sup>a</sup>Cemented treated layer.

<sup>b</sup>Estimated by authors.

when the applied stress approaches its bearing capacity. Most of the literature has indicated that the failure mode observed in the field is plastic deformation instead of fatigue cracking (8, 22); that is, when high stresses are produced at some point in the layer, the bonds produced by stabilizing agents are broken and the mix continues behaving as an untreated material in that specific area.

On the basis of these observations, it is possible to state that the different trends of the stiffness evolution could be explained by the stress state of the FB layer. To support this assumption, a simple multilayered linear elastic model was used to calculate stresses and strains in the FB layer in the Greek and South African projects. Dual truck tires were modeled with two 20-kN loads separated by 350 mm and with a contact pressure of 700 kPa. In both projects, stresses and strains were calculated at one-quarter of the thickness of the FB layer measured from the bottom of the FB layer. Table 1 shows details of the materials' elastic properties and thicknesses for each pavement structure evaluated, as well as stresses and strains calculated at one-quarter of the FB layer thickness. The indirect tensile strength (ITS) of the FB mix was assumed to be 300 kPa in both projects, which is considered a representative ITS of a mix with a 1.0% cement content.

On the basis of the results obtained from the pavement structural analysis, it can be seen that the FB layer of the pavement structure in Greece was subjected to a stress ratio (SR) of 0.20, while the FB layer of the pavement structure in South Africa was subjected to an SR of 0.55. These two values are quite different and could explain the behavior observed by using the concepts for the thickness design of perpetual pavements (23). The perpetual pavements concept, which is also a universal structural concept, states that, if the deformations that occur at critical points are below a specific value (endurance limit), then the asphalt layer will not suffer fatigue and therefore its structural lifetime could be extended to periods of even 50 years. Under this scenario, only functional maintenance actions should be taken to keep the road standard expected. Results of studies performed to validate this affirmation have suggested that the limiting tensile strain at the bottom of the asphalt concrete layers should be no greater than 60  $\mu\epsilon$  and that at the top of the subgrade the vertical strain should be limited to 200  $\mu\epsilon$ . By using a similar approach on FB layers, it may be assumed that, if SR is lower than the endurance limit, then the FB will maintain its stiffness.

On the basis of the preceding discussion, it is expected that after a period the FB stiffness plateaus, but this depends on the stress–strain levels applied to the layer, in a way similar to the behavior

observed in the pavements analyzed in this paper. In the case of the pavement structure in Greece, it is probable that an SR of 20% is lower than the SR required for generating some damage to the bonds or mastic produced by the bitumen and cement particles.

This paper presents results of research work performed to represent and quantify the stiffness evolution of FB mixes subjected to different SR levels. This information was used for two purposes:

- To establish the effect of the different bitumen and cement contents on the long-term performance of the FB mixtures so as to determine the appropriate content of each one and
- To define the maximum stress level that must be accepted in the FB layer to maintain a constant stiffness.

## LABORATORY TESTING PROGRAM

### Materials

#### *Properties of Reclaimed Asphalt Pavement and Granular Materials*

The recycled asphalt pavement (RAP) used was collected from the Huequén–Los Sauces recycling project, located south of Santiago, Chile (Region IX). Only the RAP was pulverized by the recycler machine. The RAP was then mixed with reclaimed granular materials in the laboratory to simulate the same conditions found in recycled projects in Chile. The mix of RAP and reclaimed granular materials formed the recycled asphalt granular (RAG) materials used in this study. One gradation was constituted from the original material by sieving the RAP into three fractions and recombining them with reclaimed granular base materials for laboratory testing. In addition, inert baghouse dust collected from an asphalt concrete plant was used for correcting the final RAG mix. The main properties of the RAG materials were these:

- Maximum aggregate size: 19 mm,
- Material passing No. 200 sieve (0.075 mm): 6%,
- Material passing No. 40 sieve (0.425 mm): 13%,
- Material passing No. 4 sieve (4.75 mm): 46%,
- Crushed–fractured particles: 100%,
- Plasticity index: nonplastic,
- Optimum moisture content: 6.0%, and
- Maximum density: 2,190 kg/m<sup>3</sup>.

Properties of Stabilizing Agents

Bitumen properties were as follows:

- Absolute viscosity (at 60°C): 3,210 poise,
- Ductility (at 25°C): >150 cm at 5 cm/min,
- Penetration index: -0.9, and
- Flash point: 360°C (Cleveland open cup).

In addition, on the residual bitumen, viscosity (at 60°C) from the thin-film oven test was 9,180 poise and ductility (at 25°C) was >150 cm at 5 cm/min. Portland cement Type II was used in the preparation of all mixes.

Mixing Preparation, Compaction, and Curing

The RAG material was foamed by using the Wirtgen WLB-10 laboratory at 165°C, with 2.5% of foaming water by mass. The expansion ratio was approximately 12 to 15, and the half-life was 10 to 12 s. RAG was preconditioned by placing buckets with 20 kg of material at uncontrolled laboratory temperature (between 18°C and 25°C) and relative humidity (between 35% and 55%).

Before mixing, the optimum moisture content of the RAG material was strictly controlled and on average was near 75% of the optimum moisture content of the RAG mix. Several Proctor tests were conducted to define the optimum moisture content value. RAG materials and stabilizing agents were mixed by using a twin-shaft pug mill mixer. During mix production, RAG materials were combined dry with the active filler, followed by the addition of water. After 1 min of mixing, FB was injected while the RAG material was being agitated. ITS specimens 150 mm in diameter and 60 mm high were prepared and compacted by using gyratory compaction. The compaction procedure was adjusted to obtain the same density in each specimen. Specimens were extruded from the molds immediately after compaction and cured in a forced-air oven at 40°C for 72 h.

Laboratory Tests

The stress-controlled indirect tensile fatigue test (ITFT) was used to evaluate the stiffness evolution of the FB mixes. This test uses the same setup of the ITS test with cyclic loads. Linear variable differential transformers (LVDTs) were installed diametrically to measure horizontal tensile strain (Figure 3), which is used to calculate the dynamic-elastic modulus as well as the fatigue performance of the mix. The stress level applied in the ITFT was represented by using the SR concept, which is defined as the quotient between the tensile stress ( $\sigma_x$ ) and the ITS. The strains measured by the LVDTs were used for calculating the dynamic modulus (stiffness,  $S$ ) of the mix. The following equations were used:

$$\sigma_x = \frac{2P}{\pi td} \tag{1}$$

where

- $P$  = vertical load,
- $t$  = thickness of specimen, and
- $d$  = diameter.

$$S = \frac{\sigma_x}{\epsilon} \tag{2}$$

where

- $S$  = elastic modulus,
- $\sigma_x$  = effective tensile stress, and
- $\epsilon$  = measured tensile strain.

$$SR = \frac{\sigma_x}{ITS} \tag{3}$$

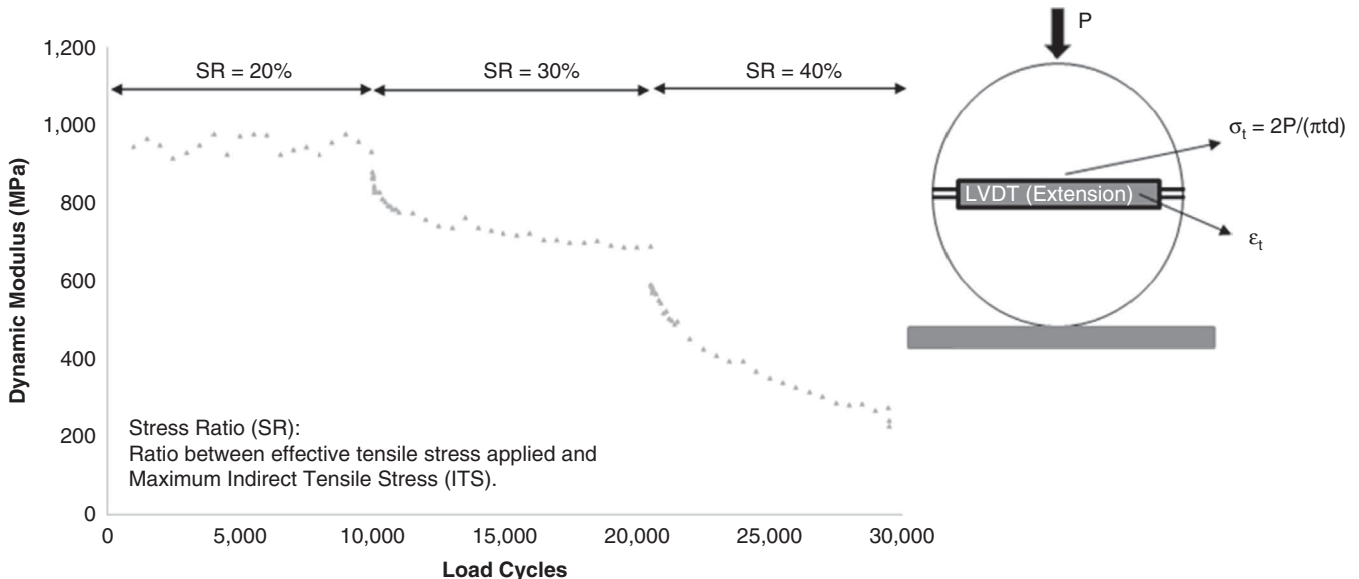


FIGURE 3 Example of ITFT.

**TABLE 2** Experimental Design for Measurement of Stiffness Evolution

Variable	No. of Levels	Values
RAG source	1	NA
Bitumen grade	1	AC-24
Foaming properties	1	165°C, 2.5% foaming water
Foamed bitumen content	3	1%, 2%, and 3%
Cement content	3	0%–1%–2%
Compaction effort	1	Gyratory compaction
Curing period	1	72 h at 40°C
Water conditioning	1	Dry
ITFT replicates	2	Test carried out at 25°C
Stress-state levels	4	Stress ratio equal to effective stress/ITS

NOTE: NA = not available.

Figure 3 shows how the stiffness of the mix decreases due to the progressive increase in plastic and elastic deformations under cyclic loading.

### Experimental Design

The laboratory test program using the ITFT was designed to study the impact of the bitumen and cement contents. In addition, the ITFT results attempt to define the maximum stress level that the FB layer is capable of withstanding without significantly reducing stiffness. Four stress levels, defined by using SR, were applied to each specimen. At each SR, 5,000 load cycles were applied, for a total of 20,000. ITFTs were performed at 25°C in a temperature-controlled cabinet. The experimental design for this study is summarized in Table 2.

**TABLE 3** Mixes Evaluated in This Research

Mix	FB Content (%)	Cement Content (%)
FB1C1	1.0	1.0
FB2C1 <sup>a</sup>	2.0	1.0
FB3C1	3.0	1.0
FB2C0	2.0	0.0
FB2C1 <sup>a</sup>	2.0	1.0
FB2C2	2.0	2.0

<sup>a</sup>Same mix.

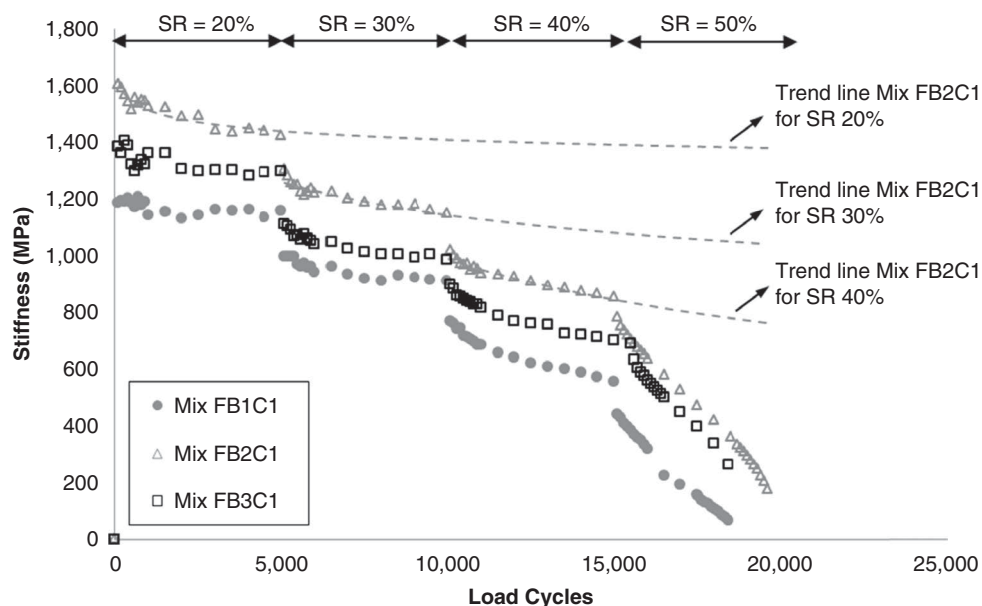
Of the 12 mixes of the factorial design presented, five were selected for testing. Mixes FB1C1, FB2C1, and FB3C1 were tested to evaluate the effect of the FB content, and mixes FB2C0, FB2C1, and FB2C2 were tested to evaluate the effect of the cement content (Table 3).

## ANALYSIS OF RESULTS

### Effect of Foamed Bitumen Content on Stiffness Evolution

Figure 4 shows results of the ITFT performed on Mixes FB1C1, FB2C1, and FB3C1 to evaluate the effect of the bitumen content on stiffness evolution. Results correspond to the average of two specimens evaluated.

Trend lines were fitted and extrapolated to the measured modulus for each mix and for each SR to estimate the stiffness of additional load cycles. Examples of trend lines for Mix FB2C1, loaded at different SRs, are shown in Figure 4. Table 4 shows details of trend lines of each mix as well as the expected stiffness at 100,000 and 1,000,000 load cycles. In addition, the quotient between the initial



**FIGURE 4** ITFT stiffness evolution of mixes with different bitumen contents.

TABLE 4 Details of Trend Lines for Each Mix and Estimated Stiffness

Mix	Stress Ratio	$y = a * x^b$		$R^2$ (%)	Long-Term Stiffness and RSIE for $i$ Cycle Loads	
		$a$	$b$		$i = 100,000$ (RSIE)	$i = 1,000,000$ (RSIE)
FB1C1 (1% FB + 1% cement)	20	$c$	-0.013	50.7	1,098 (92%)	1,066 (89%)
	30	$c$	-0.136	83.4	654 (55%)	478 (40%)
	40	$c$	-0.755	96.6	131 (11%)	23 (2%)
FB2C1 (2% FB + 1% cement)	20	$c$	-0.031	88.5	1,310 (82%)	1,220 (76%)
	30	$c$	-0.140	85.3	828 (52%)	600 (38%)
	40	$c$	-0.384	94.5	407 (25%)	168 (11%)
FB3C1 (3% FB + 1% cement)	20	$c$	-0.019	61.2	1,220 (87%)	1,168 (83%)
	30	$c$	-0.157	90.1	682 (49%)	475 (34%)
	40	$c$	-0.581	96.3	228 (16%)	60 (4%)
FB2C0 (2% FB + 0% cement)	20	$c$	-0.031	70.2	849 (85%)	791 (79%)
	30	$c$	-0.261	95.1	341 (34%)	187 (19%)
	40	NA	NA	NA	NA	NA
FB2C1 (2% FB + 1% cement)	20	$c$	-0.031	88.5	1,310 (82%)	1,220 (76%)
	30	$c$	-0.140	85.3	828 (52%)	600 (37%)
	40	$c$	-0.384	94.5	407 (25%)	168 (10%)
FB2C2 (2% FB + 2% cement)	20	$c$	-0.013	61.2	1,538 (90%)	1,493 (88%)
	30	$c$	-0.139	90.1	844 (50%)	613 (36%)
	40	$c$	-0.576	96.3	324 (19%)	86 (5%)

NOTE:  $y$  = stiffness of the indirect tensile fatigue/modulus test;  $x$  = load cycles;  $c$  = constant value not used in the analysis. NA = not available due to failure.

and long-term stiffness (RSIE) is also presented in Table 4. A couple of tests were performed by using more than 100,000 cycles so as to verify the extrapolation made.

From the results of Figure 4 and Table 4, the following observations are made:

- In general, all mixes show similar trends in relation to stiffness evolution at different SRs. On the basis of the results presented in Table 4, curves were fitted to measured values. The curves are described by a power relationship with regression coefficients:  $a$  and  $b$ . Table 4 shows that  $b$  coefficients are quite similar; for example, when an SR of 30% was applied, the  $b$  coefficients for Mixes FB1C1, FB2C1, and FB3C1 were -0.136, -0.140, and -0.157, respectively. However, when SRs of 20% and 40% were applied, a larger variability was observed, but  $b$  values were within the same range.

- The stiffness of the FB mixes plateaus after a certain number of load cycles when the SR is around 20%. For example, Mix FB2C1 showed a relatively constant long-term stiffness of 1,200 to 1,300 MPa, which represents almost 80% of the initial stiffness (1,600 MPa). In the case of an SR equal to 30%, the mix showed a good evolution of stiffness, with a constantly decreasing line with a low slope. In this case, the stiffness of the mix after 1 million load cycles was 600 MPa, which represents 37.5% of the initial stiffness (1,600 MPa). This fact showed that, after all the load cycles were applied, the mix still was able to keep cohesion because of the effect of the stabilizing agents. Similar results were observed in Mixes FB1C1 and FB3C1. In the case of an SR equal to 40%, mixes showed a clear reduction in stiffness with load cycles. All showed almost null stiffness after 1 million cycle loads.

- When mixes were subjected to an SR of 50%, specimens collapsed in a relatively short period, indicating that stresses and strains applied are much larger than the cohesion provided by the FB and cement to the mix.

- Although trends of the stiffness for each mix were quite similar, results showed that there was an optimum bitumen content at which stiffness was maximized. In this case, the best results in relation to stiffness evolution were observed in Mix FB2C1 with 2% FB and 1% cement.

- Table 5 shows the slope of the trend line for each mix when SR is 50%. When mixes were subjected to an SR of 50%, the change of stiffness rate for each mix was quite similar, which means that the FB content did not significantly affect the performance of the mix under these stress conditions.

### Effect of Cement Content on Stiffness Evolution

Figure 5 shows results of the ITFT performed on Mixes FB2C0, FB2C1, and FB2C2 to evaluate the effect of the cement content on stiffness evolution. Results correspond to the average of two specimens.

TABLE 5 Slope of Trend Lines for SR Equal to 50%

Mix	Stress Ratio (%)	Slope ( $m$ ) ( $y = m * x + b$ )
FB1C1	50	-0.1116
FB2C1	50	-0.1207
FB3C1	50	-0.1189
FB2C0	40 <sup>a</sup>	-0.0643
FB2C1	50	-0.1207
FB2C2	50	-0.2183

<sup>a</sup>FB2C0 collapsed for SR equal to 40%.

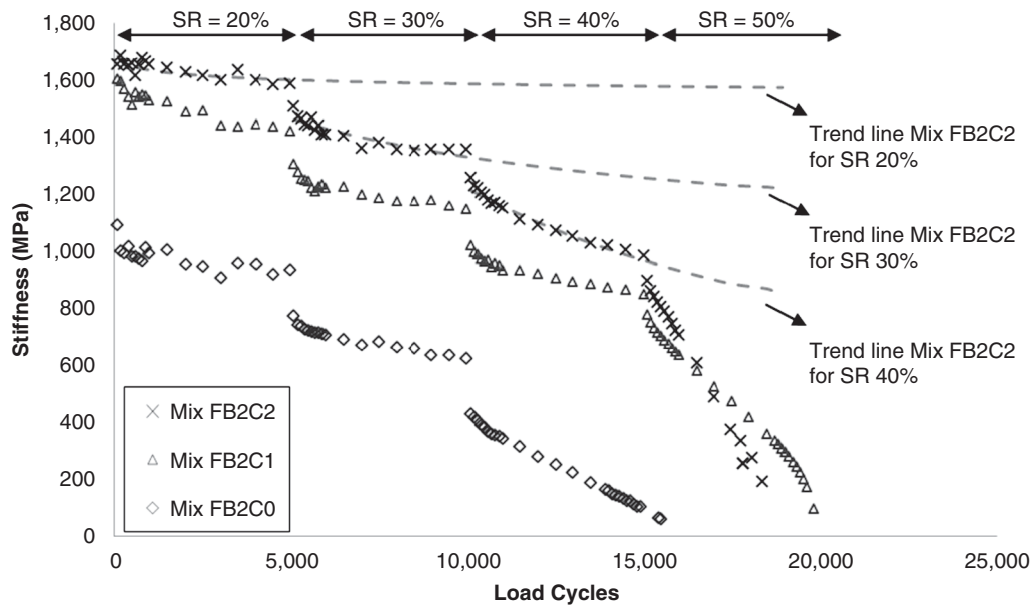


FIGURE 5 ITFT stiffness evolution of mixes with different cement contents.

Trend lines were fitted and extrapolated to the measured modulus for each mix and for each SR to estimate the stiffness of additional load cycles. Examples of trend lines for Mix FB2C2, loaded at different SRs, are shown in Figure 5. Table 4 shows details of the trend lines of each mix as well as the expected stiffness at 100,000 and 1,000,000 load cycles. In addition, the RSIE was included in Table 4. A couple tests were performed by using more than 100,000 cycles so as to verify the extrapolation made.

From the results of Figure 5 and Table 4, the following observations are made:

- Significant differences exist between mixes without cement (Mix FB2C0) and with cement (Mixes FB2C1 and FB2C2) for the same bitumen content. Mixes with cement (FB2C1 and FB2C2) have higher stiffness than Mix FB2C0 (with FB only). While stiffness of mixes FB2C1 and FB2C2 was 1,310 and 1,538 MPa, respectively, for 100,000 cycles, stiffness for Mix FB2C0 was 849 MPa. These results indicate that a pavement structure with FB2C1 and FB2C2 layers will have a better structural capacity than a structure that uses Mix FB2C0.

- Furthermore, Mixes FB2C1 and FB2C2 were able to withstand more cycles than mix FB2C0 for the same test-loading sequence. While Mix FB2C0 collapsed for an SR equal to 40%, Mixes FB2C1 and FB2C2 collapsed for an SR equal to 50%.

- The stiffness of the FB mixes plateaus after a certain number of load cycles when the SR is on the order of 20%, providing assurance that the mix will keep its cohesion in the long term.

- For the case of an SR equal to 30%, mixes with cement (FB2C1 and FB2C2) showed an acceptable stiffness evolution. Although Mix FB2C2 initially had a greater stiffness than Mix FB2C1, when extrapolated to 100,000 cycles, the stiffness of both mixes tended to be the same. Stiffness of Mix FB2C1 was equal to 828 MPa for 100,000 extrapolated cycles, while stiffness of Mix FB2C2 for the same conditions was 844 MPa.

- For the case of an SR equal to 40%, Mix FB2C1 showed a better stiffness evolution than Mix FB2C2. In this case, the stiffness rate of

change for Mix FB2C2 was significantly higher than that for Mix FB2C1, which gave lower stiffnesses in the long term. When trend lines fitted to the data were compared, the values of the variable  $b$  were  $-0.384$  for Mix FB2C1 and  $-0.576$  for Mix FB2C2. If the fitted equations were used to extrapolate the stiffness, at 1 million load cycles, the stiffness of Mix FB2C1 would be 168 MPa, while the stiffness of Mix FB2C2 would be 86 MPa. In contrast, Mix FB2C0 (with only FB) collapsed for an SR equal to 40%.

- Table 5 shows trend lines fitted to the data for an SR equal to 50% in Mixes FB2C1 and FB2C2 as well as an SR equal to 40% in Mix FB2C0. Slopes ( $m$ ) for each equation indicated that, as the cement content increased, the rate of change of the stiffness also increased. This relationship means that, when cement content increases, mixes with poor behavior are obtained for an SR of 50%.

- Overall, the use of 2.0% cement in an FB layer will be beneficial only if the FB layer is loaded to an SR equal to or lower than 30%. If the FB layer is loaded to an SR equal to or higher than 40%, the use of only 1.0% cement together with FB is recommended.

## CONCLUSIONS

An analysis of the stiffness evolution of foamed bitumen mixtures was done by using the ITFT with the aim of identifying the evolution of the elastic modulus or stiffness of the mixture in the long term. The experimental study was designed to obtain the maximum stress level that the FB layer is capable of withstanding without significantly reducing its stiffness, as well as to study the effect of the bitumen and cement contents in the long-term stiffness evolution. On the basis of the results presented, the main conclusions may be summarized as follows:

- The stiffness of FB mixes will evolve in accordance with the stress level applied to the FB layer. If the stress level is lower than a specific value, the stiffness of the mix will remain constant at a value quite close to the initial stiffness. If the stress level is greater than a specific value, the stiffness of the mix will gradually decrease.

- If the SR of the mix is lower than 20%, then the mix will have stiffness within a range of 75% to 90% of the initial stiffness after 1 million load cycles. The value will keep relatively constant during the life of the pavement.

- If the SR of the FB mix layer is between 20% and 40%, the stiffness will gradually decrease. The higher the SR is, the higher will be the reduction rate of the stiffness.

- If the SR is around 50%, then the mix will collapse and the cohesion provided by stabilizing agents will reduce to 0 in a relative short period. In this case, the stiffness will be equivalent to the elastic-resilient modulus of the reclaimed material without stabilizing agents.

- Analysis of the bitumen content effect showed extremely little influence on the stiffness evolution, but it was possible to find an optimum content that maximizes stiffness; in this case, Mix FB2C1, which was followed by Mixes FB3C1 and FB1C1. Conversely, the effect of cement content was significant on the stiffness evolution as well as on the absolute value of stiffness. In addition, cement must always be incorporated into FB mixes to guarantee minimum short- and long-term stiffness.

- Results showed that the use of 2% cement in the FB layer would be beneficial only if the FB layer was loaded to an SR equal to or lower than 30%. If the FB layer is loaded to an SR equal to or higher than 40%, the addition of only 1.0% cement and FB is recommended.

The data and analysis provided in this research can be used to estimate an effective elastic modulus of the FB mix in the long term on the basis of the stress state expected at the FB layer. The effective elastic modulus may be defined as a percentage of the initial stiffness, and a shift factor must be developed to adapt the elastic modulus provided by the ITFT to the elastic modulus that better represents the mechanical properties of the FB mix in the field.

The laboratory work presented in this paper was performed by using only one aggregate source, one bitumen source, a single active filler, and a single temperature. All these factors contribute significantly to the performance of the FB mix, and therefore results obtained are limited. Conclusions must be validated by using a larger experimental design.

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The Chemical and Mechanical Stabilization Committee peer-reviewed this paper.