Evaluation of Additional Laboratory Tests for Design of Full-Depth Reclamation Mixtures Using Foamed Bitumen

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The mix proportion design methods for full-depth reclamation mixtures using foamed bitumen normally fix a constant active filler content, and an indirect tensile strength (ITS) test is used to determine the optimum bitumen content. However, it has been reported in the literature that for some materials the ITS test is not sufficiently sensitive to bitumen content. This lack of sensitivity is a problem for the practitioner engineer who has to validate the bitumen content adopted in the mixture design. The main objective of this work is to examine the sensitivity to bitumen content of additional laboratory tests that could complement current design methods based on ITS. The mixtures used in the study were prepared by using three recycled blends of reclaimed asphalt pavement and aggregate that were mixed with bitumen foam contents of 1.25%, 2.5%, and 3.75%. Test results confirmed the low sensitivity of the ITS test, and it was found that the indirect tensile fatigue (ITF) test was the most sensitive among all tests. To explain the higher sensitivity of the ITF test compared with the ITS test, a stress–strain diagram and a simple unidirectional mechanical model were developed. In addition, an *S-N* fatigue diagram was used to illustrate that at a larger number of load cycles, the effect of the foamed bitumen content is clear, as shown in the experimental work. Overall, the laboratory program and material behavior analysis indicate that when the ITS test does not provide conclusive results, the laboratory program should be complemented with ITF tests to determine the optimum foamed bitumen content with more reliability.

Full-depth reclamation (FDR) using foamed bitumen (FB) is a widely used flexible pavement rehabilitation technique. FDR has several advantages compared with traditional rehabilitation techniques from environmental, economic, and social perspectives. For example, it has been shown that energy consumption in FDR projects using FB is lower than in projects where traditional techniques (i.e., asphalt overlay, pavement reconstruction) are adopted (*1*). FDR using FB is carried out by mobile pavement recyclers that produce bitumen foam. During construction, recyclers mill the asphalt concrete layer and the upper portion of the unbound granular base and simultaneously add bitumen foam, active filler (AF), and water to achieve optimum moisture compaction. Normally, this process results in a mixture with approximately one-third of reclaimed asphalt pavement (RAP) and two-thirds of reclaimed unbound granular material (UGM). In FB mixtures with RAP the added bitumen content normally ranges between 2% and 3% by weight of the RAP–UGM blend. Portland cement is commonly used as AF, with the objective of increasing the early strength and reducing the moisture sensitivity of the FB mixtures.

PROBLEM WITH DESIGN OF FB MIXTURES

The main objective of the mixture design is to determine the optimum FB content to be added to the RAP–UGM reclaimed materials and guarantee a minimum strength under dry and soaked conditions. Normally, the AF content is fixed to 1% and the optimum bitumen content is determined by mixing the virgin RAP–UGM material with different bitumen content levels and measuring the strength of each mixture (*2–4*). The mechanical test generally carried out in the laboratory mixture design is the indirect tensile strength (ITS) test under dry and soaked conditions (Figure 1*a*). In the ITS test, cylindrical specimens (100 mm or 150 mm in diameter) are loaded diametrically up to failure or maximum load. The content of ITS versus FB is plotted and design curves are fitted to the data (Figure 1*b*).

The bitumen content that yields the highest strength under soaked or dry conditions or the bitumen content that yields the highest ratio between dry and soaked ITS conditions is in general considered to be the optimum bitumen content. However, it has been observed and reported in the international literature that ITS values do not significantly change for different FB contents (*5–10*). Furthermore, sometimes dry and soaked ITS tests are much less sensitive to FB content than AF; this result makes it difficult to justify the benefits of using FB to road authorities.

Typical trends of ITS tests for mixture designs obtained by the authors from local projects are presented in Figure 1*b,* where each data point is an average of three tests. Results show that dry ITS tests between 2% and 3.5% are very similar with a variation of only approximately 25 kPa, whereas the soaked ITS test fluctuates by only 50 kPa. Conversely, the ratio between dry and soaked ITS, or the tensile strength ratio, shows a variation of less than 5% between all bitumen contents. In other words, it is a problem for the engineering practitioner to validate the design bitumen content since normally ITS tests show low sensitivity to bitumen content.

OBJECTIVES AND SCOPE

The objectives of this work are (*a*) to examine the sensitivity to bitumen content of other laboratory tests that could complement current design methods for FB mixtures and determine the optimum FB con-

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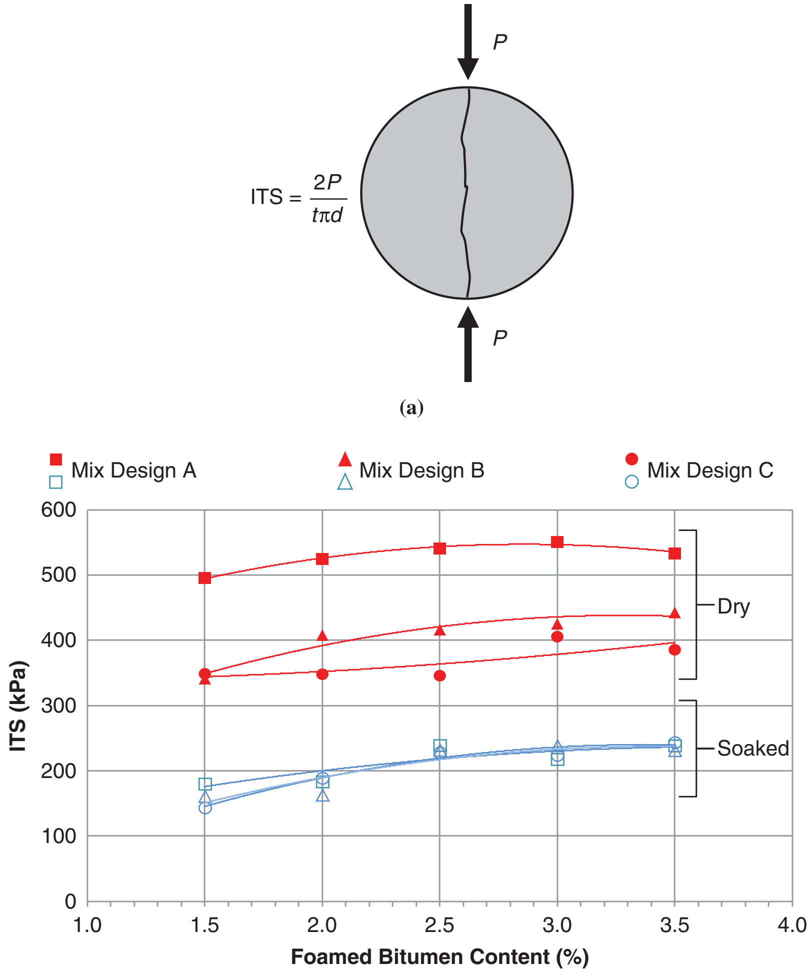


(a)

(b)

FIGURE 1 ITS test data: (*a*) cylindrical specimen loaded diametrically (P = load, t = specimen thickness, d = specimen diameter) and (*b*) typical mixture design curves of local FB projects. Open symbols indicate soaked tests and solid symbols indicate dry tests.

tent with more certainty and (*b*) to better understand the behavior of the material under different loading regimes and its effect on the laboratory results. Complementary laboratory tests could help engineers who are not experts in FB design to better define the optimum FB content in road construction projects and to improve the reliability in the design and performance of this type of pavement material.

The study was limited to road conditions found in Chile, where most of the FDR projects using FB have been carried out in distressed pavements with relatively thin (50 to 80 mm) hot-mix asphalt and good-quality base and subbase layers. These conditions are found in many other countries (e.g., Australia, New Zealand, and South Africa and roads with moderate to low traffic in the United States) and yield RAP–UGM blends with about one-third RAP and two-thirds UGM.

STUDY METHODOLOGY

The methodology followed in the study consisted of an initial review of the literature to see the reported effects of bitumen content in the results of different laboratory tests. A particular focus was given to mixtures with less than 50% RAP for consistency with local conditions. Later, a laboratory-based experimental program was designed and performed in which the sensitivity of bitumen content was studied for different laboratory tests. Finally, a conceptual mechanical model was used for interpretation of the mixture behavior, as detailed later.

LABORATORY EXPERIMENTAL PROGRAM

The laboratory program consisted of studying and comparing the sensitivity to bitumen content of four different laboratory tests. The tests used in the research program were ITS and unconfined compressive strength (UCS) and the less common triaxial resilient modulus (TxMr) and ITF tests. Most of the mixtures were prepared with bitumen contents of 1.25%, 2.5%, and 3.75% and 1% portland cement of the dry mass of the aggregates. A few specimens were prepared without portland cement and at bitumen contents of 1.83% and 3.13% for ITS tests. Details of the mixtures prepared for each laboratory test and testing conditions are presented in Table 1.

TABLE 1 Details of Mixtures and Testing Conditions Adopted in Laboratory Program

	Cement (%)		Bitumen (%)						Condition	
Test	0	1	0.00	1.25	1.83	2.75	3.13	3.75	Dry	Soaked
ITS	•	—	•	•	•	•	•	•	•	•
	—	•	—	—	—	•	—	•	•	•
UCS	—	•	—	•	—	•	—	•	•	•
TxMr	—	•	—	•	—	•	—	•	•	•
ITF	—	•	—	•	—	•	—	•	•	—

NOTE: Solid circles represent laboratory tests that were carried out and mixtures prepared in laboratory as part of experimental program. Dashes = tests not performed under these conditions.

Materials

RAP was obtained by milling from a pavement rehabilitation project near Santiago, whereas the UGM was provided by a local asphalt company. The RAP and the UGM were sieved and separated into 11 different sizes and later blended to create three mixtures with different particle size distributions. Although this process was labor intensive, it was deemed important in order to reduce the variability associated with grading.

The combinations of RAP and UGM were prepared with the objective of simulating three common scenarios of FDR projects. The main difference between gradations was the amount of fine particles in the mix: 5%, 10%, and 15%. The three gradations (Figure 2) were defined according to their fine particle content: A5 (5% fines), B10 (10% fines), and C15 (15% fines). Blends A5, B10, and C15 were in accordance with the grading envelopes proposed in the TG2 guidelines (*2*). The optimum moisture content for blends A5, B10, and C15 were 6.2%, 6.6%, and 6.4%, respectively, calculated by using a modified Proctor test. The maximum dry densities obtained from these tests are 2.220 t/m^3, 2.245 t/m^3, and 2.225 t/m^3. The proportion of RAP:UGM by mass was approximately 0.33.

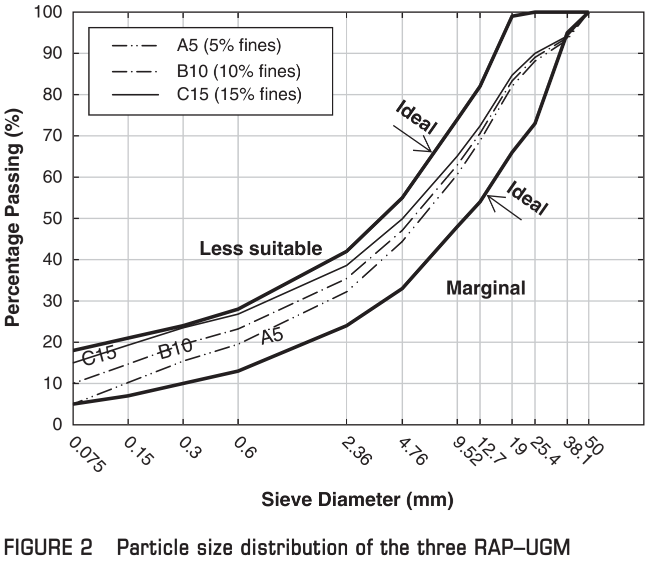


FIGURE 2 Particle size distribution of the three RAP–UGM combinations.

Bitumen and Foam Characteristics

The bitumen used in the research was a CA24 (equivalent to a PG 64-16) widely used in local FDR projects. The foam properties of the bitumen are an expansion ratio of 23, a half-life ($\tau^{1/2}$) of 7 s, a foam index of 286, a foaming water value of 3.5%, and a temperature of 160°C (*11*). Portland cement was chosen as the AF. The amount of AF was set at 1%, which is the practice in local FDR projects and technical guidelines (*2*).

Mixing

A Wirtgen WLB 10 was used for binder foaming, and the equipment for the mixing process was a WLM 30. The aggregate was conditioned to 20°C to 25°C before mixing for at least 12 h and then placed in the WLM 30. Compaction water was added to approximately equal the 70% to 80% of the optimum moisture content. Bitumen was first heated in the oven up to a temperature of 120°C the day before mixing. The bitumen was placed into the WLB 10 kettle and the temperature was raised to 160°C. Foaming water was set to a flow equivalent of 3.5% of the bitumen weight. Once compaction water and AF were added, the mixer was switched on for at least 2 min before the bitumen was discharged. The mixing time was 60 s for all the FB mixtures.

Compaction, Curing, and Testing Conditions

The different compaction methods shown in Table 2 were adopted for each type of test. All specimens were cured for 72 h in a

TABLE 2 Specimen Dimensions, Compaction Type, Effort, and Quantity Applied

Specimen	Dimensions	Compaction
ITS, ITF	Cylindrical (ϕ = 101.6 mm; h = 63.5 mm)	Marshall hammer, 75 blows per face
UCS	Cylindrical (ϕ = 100 mm; h = 115 mm)	Modified Proctor, 25 blows, 5 layers
TxMr	Cylindrical (ϕ = 100 mm; h = 200 mm)	Modified Proctor, 56 blows, 5 layers

NOTE: ϕ = diameter of specimen; h = height of specimen.

forced-air oven at 25°C. Soaked specimens were submerged in water at 40°C for 24 h. Specimens were conditioned at 20°C for at least 12 h before testing. Testing was performed at a controlled room temperature of 20°C to 25°C.

Test Methods

ITS, UCS, and TxMr are standard and well-known pavement tests and therefore no further description will be given here. TxMr followed the AASHTO T-307 99 standard in which 15 stress stages consisting of 200 cycles are applied after a first preconditioning stage of 500 cycles. The ITF test was applied following European Standard EN 12697-24. The ITF test has a similar setup to that for the ITS test (Figure 1*a*), with specimens 100 mm in diameter loaded diametrically with a cyclic vertical compressive force controlled by using a universal testing machine. To obtain the fatigue life, a target horizontal tensile stress of 240 kPa was applied to specimens thousands of times up to failure. In this test the initial dynamic vertical deformation and the number of cycles were recorded. Results are reported as the percentage increase from the initial dynamic vertical deformation. ITF tests have been adopted by other researchers on FB (*12, 13*).

ANALYSIS OF TEST RESULTS

ITS and UCS Tests

Mixtures with 1% Cement

Figure 3*a* shows the results of ITS specimens prepared with the three aggregate blends and mixed with bitumen contents of 1.25%, 2.5% or 3.75%, and 1% cement. Overall average results are represented by the thick black curve and confirm the minimal effect of bitumen content on ITS when mixtures with AF are tested. A similar maximum dry ITS was found for mixtures with 1.25% and 3.75% bitumen content, and for soaked ITS the mixtures with 3.75% bitumen content gave the maximum strength.

Figure 3*b* shows the results for UCS specimens prepared with the three aggregate blends and mixed with bitumen contents of 1.25%, 2.5% and 3.75%, and 1% cement. Dry UCS results showed maximum strength with 2.5% bitumen content, and the maximum strength for soaked UCS was observed for 3.75% bitumen content. However, ITS and UCS results in general follow different trends. For example, mixtures prepared with Blend B10 yield a maximum ITS with 1.25% bitumen content, whereas the same blend yields a maximum UCS with 2.5% bitumen content.

Mixtures with 0% Cement

In addition to the mixtures prepared with 1% cement, a number of ITS specimens were prepared without AF. These mixtures were prepared on the basis of the experience and research developed by Fu et al. (*14*) and the California Transportation Department (*15*). The researchers state that FB mixtures with AF mask the effect of FB and therefore mixtures with only bitumen should be tested to clearly see the effects of the foam. With the same aggregate mixtures, A5, B10, and C15 were prepared without AF, and ITS specimens were made and tested under the same laboratory conditions applied to specimens with cement. ITS results (Figure 4) for dry conditions are on the order of 320 kPa to 450 kPa, whereas soaked ITS is on the order of a very low 20-kPa to 80-kPa range; this finding confirms that this type of FB mixture is very sensitive to moisture and that the addition of AFs is very important for the strength of the FB mixtures. C15 mixtures with the lowest bitumen contents of 1.25% and 1.83% did not survive the 24-h soaking. These results indicate that it is not always possible to soak specimens without AF to see the effects of FB.

TxMr Test

The TxMr test consists of applying different confining pressures and repeated vertical stress and measuring vertical resilient deformation. In general, the state of stress applied in this test is well below the maximum shear strength of the material tested. The resilient modulus is calculated as the ratio between the deviator stress and the vertical resilient strain. For better interpretation of the results, the 15 measured moduli were averaged and are presented in Figure 3*c*. Overall results show an increasing average modulus with increasing bitumen contents. A lower modulus was obtained for the soaked condition, as expected. Specimens prepared with Mixture C15 were damaged during soaking and were not tested.

ITF Test

Results for the ITF test are presented in Figure 5*a* (the average of three specimens). This test was conducted on Blend B10 under dry conditions identical to those for the dry ITS tests. Figure 5*b* shows details of the evolution of the ratio between actual deformation and initial deformation with the number of load cycles applied. The data indicate that the specimens sustaining the largest number of cycles before failure are prepared with 2.5% bitumen content. Three-parameter power equations were fitted to the data and are included in Figure 5*b*.

In addition to the number of cycles to failure, the deformation history in the last 1,000 to 2,000 cycles is interesting to observe (Figure 5*b*). The slope of the curve in this range was on the order of 8% to 10% for specimens prepared with 1.25% and 3.75% bitumen content, whereas for specimens prepared with 2.5% bitumen, the value was approximately 2% to 3%. The deformation rate indicates a more ductile behavior for mixtures with 2.5% bitumen content at the end of their fatigue life. In addition, the ITF test was the most sensitive to bitumen content and showed an increase of approximately 40% in the number of load cycles from 1.25% to 2.5%; this finding suggests that this test could complement the ITS test when low sensitivity to FB content is observed.

ITS MATERIAL BEHAVIOR: MONOTONIC VERSUS CYCLIC LOADING

Conceptual Composite Material Model

One of the interesting findings from the experimental results is the difference between the traditional and widely used ITS test and the ITF test, although in these tests the same specimens and load configuration are used. A conceptual model based on composite material behavior was developed to explain such a difference.

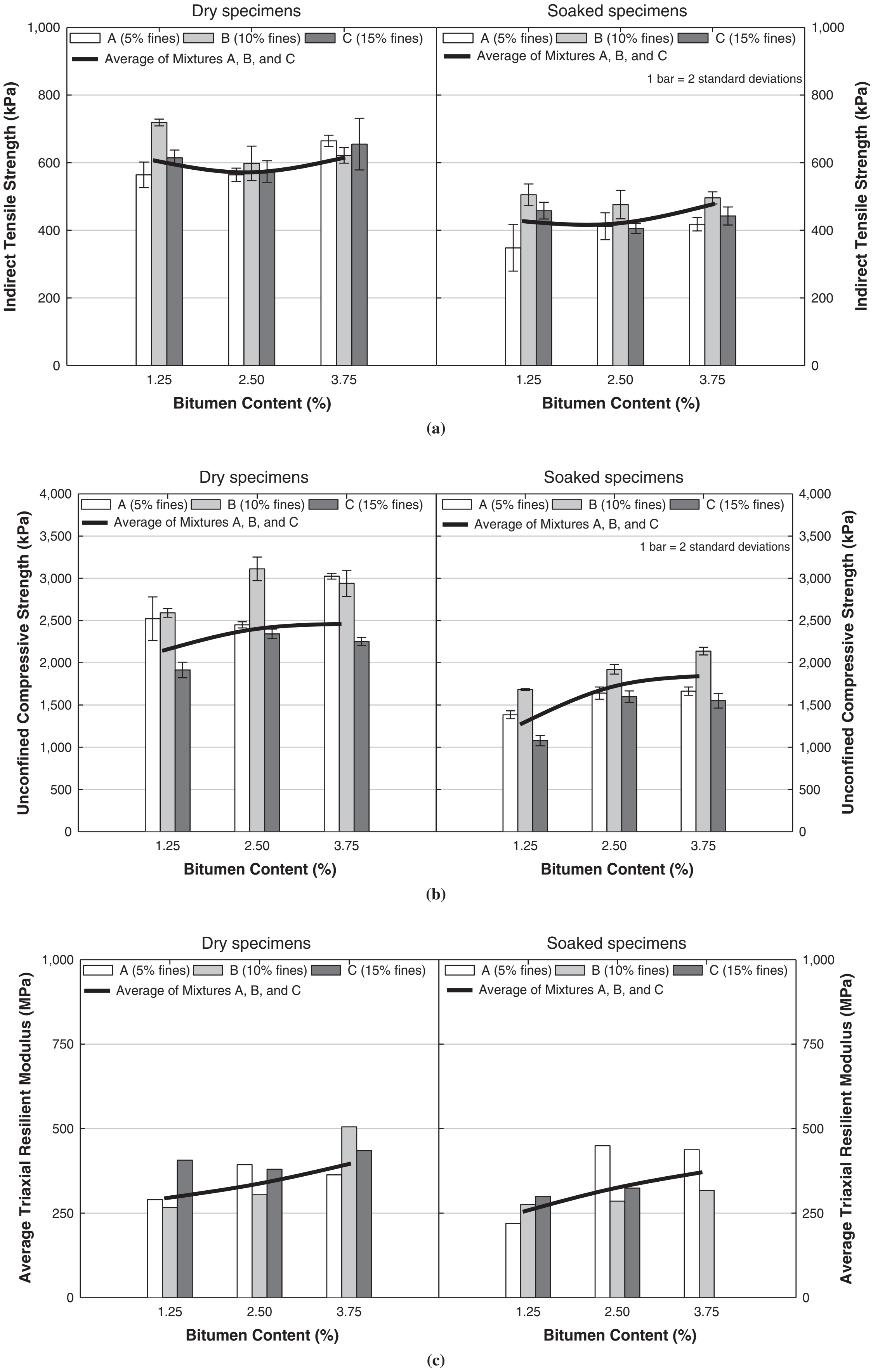


FIGURE 3 Results for dry and soaked specimens for (*a*) ITS, (*b*) UCS, and (*c*) MrTx tests.

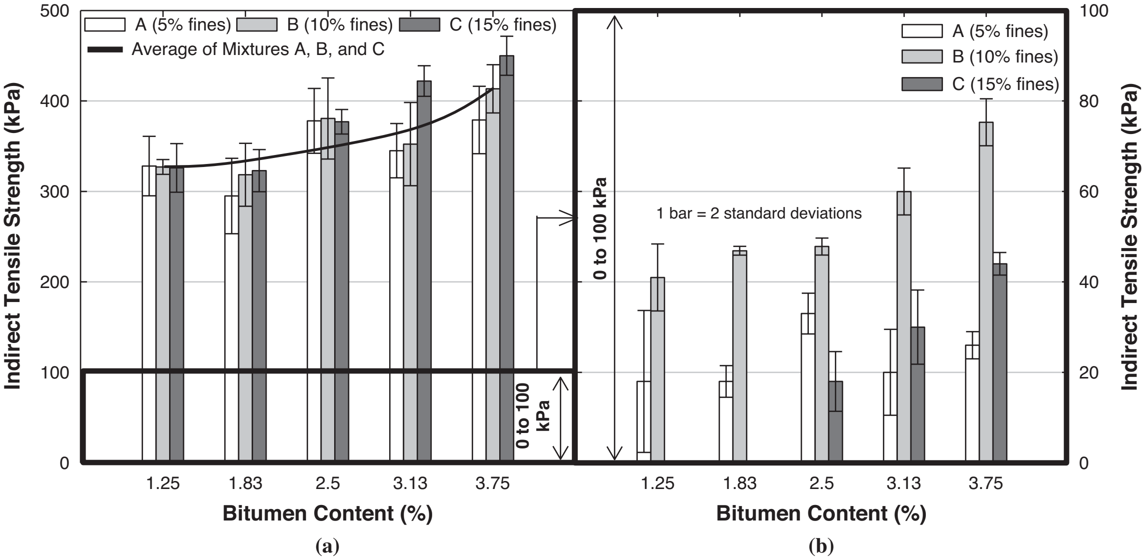


FIGURE 4 Results with 0% cement for (*a*) dry specimens (Scale from 0 to 500 kPa) and (*b*) soaked specimens (Scale from 0 to 100 kPa).

First, it is important to identify the three solid phases that compose an FB mixture (Figure 6) as originally proposed by Fu et al. (*16*):

- Aggregate skeleton, formed by large aggregate particles;
- Asphalt mastic, consisting of fine aggregate particles bonded by asphalt droplets during the FB mixing process; and
- Mineral filler, consisting of fine aggregate particles not bonded by asphalt during mixing.

Since the AF content is low (only 1%) an independent phase is not formed (*16*). Nevertheless, the AF is dispersed into the mineral filler phase and significantly increases its strength and the stiffness of the mixture, as observed in the experimental work.

When a crack propagates through an FB mixture with AF in an ITS test, it breaks through the mineral filler with the AF phase, breaks through the asphalt mastic phase, or breaks the interfaces between the asphalt mastic and aggregates (*17*). Therefore, when tensile stresses are applied, the mixture could be idealized as a composite material: the mineral filler with AF phase and the bitumen mastic phase. The behavior of these two phases is very different, with the AF being stiff and brittle and the bitumen mastic ductile. In Figure 7*a* the approximate curves of stress versus strain were drawn for the AF phase, mastic with bitumen phase, and the composite mixture. The AF curve is steep and the initiation of the fracture is produced at σ_{cu} stress and ε_{cu} strain (the letter *c* is used here on the assumption that the AF used is cement). If elastic behavior is

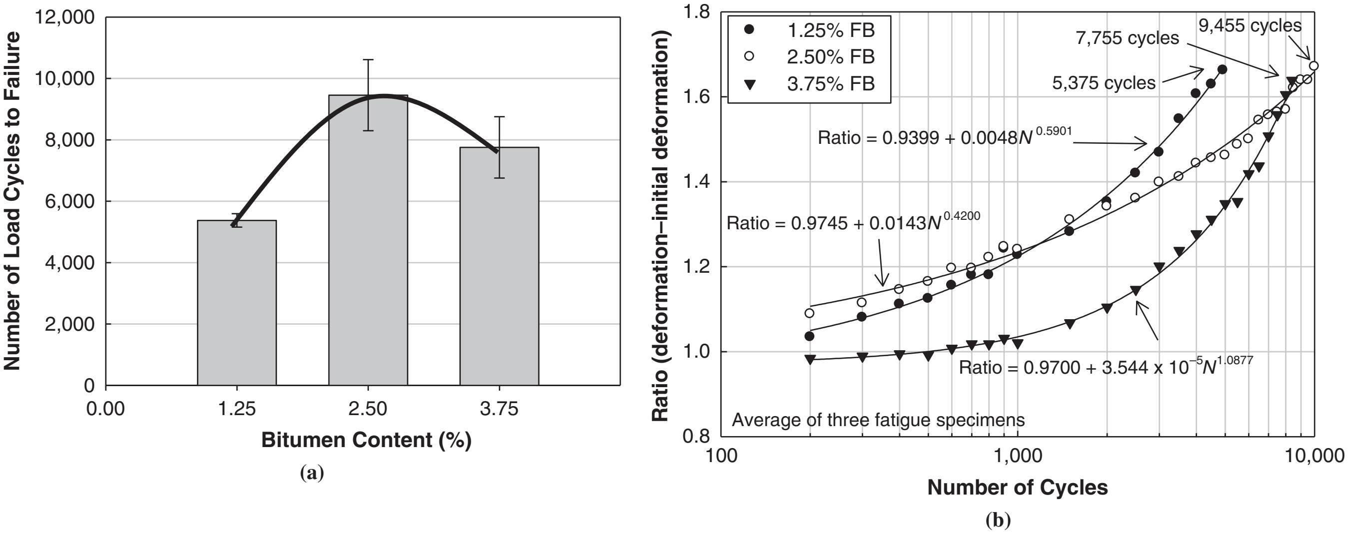


FIGURE 5 ITF test: (*a*) average of fatigue life for each mixture and (*b*) fatigue results for one set of specimens prepared with aggregate B10 and 1% cement.

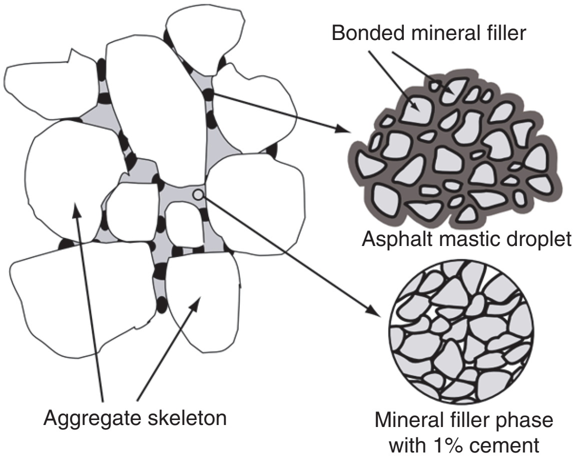


FIGURE 6 Conceptual illustration of microstructure of foamed bitumen mixture with cement [adapted from work by Fu et al. (*16*)].

assumed, the bitumen mastic can be characterized by curves with a much lower slope but higher deformability. These curves vary for different bitumen contents. If an important fraction of the fine particles is not coated by bitumen foam, the elastic modulus and strength of the mastic will be lower compared with a mastic in which the fine particles are coated with an optimum bitumen content. A lower modulus will also be observed if the bitumen content exceeds the optimum, since some bitumen will not be mixed with the fine particles of the aggregate and will behave as a lubricant, reducing the stiffness and strength of the mastic. The fracture stress and strain for the bitumen mastic with the optimum bitumen content are σ_{bu} and ε_{bu}, respectively. The composite curves in Figure 7*a* are a combination of the AF and bitumen mastic phase curves, and their stress at fracture (σ_{pu}) could be expressed by using the law of mixtures (*18*):

$$\sigma_{pu} = \sigma_{cu} V_c + \sigma_{bu}(1 - V_c) \tag{1}$$

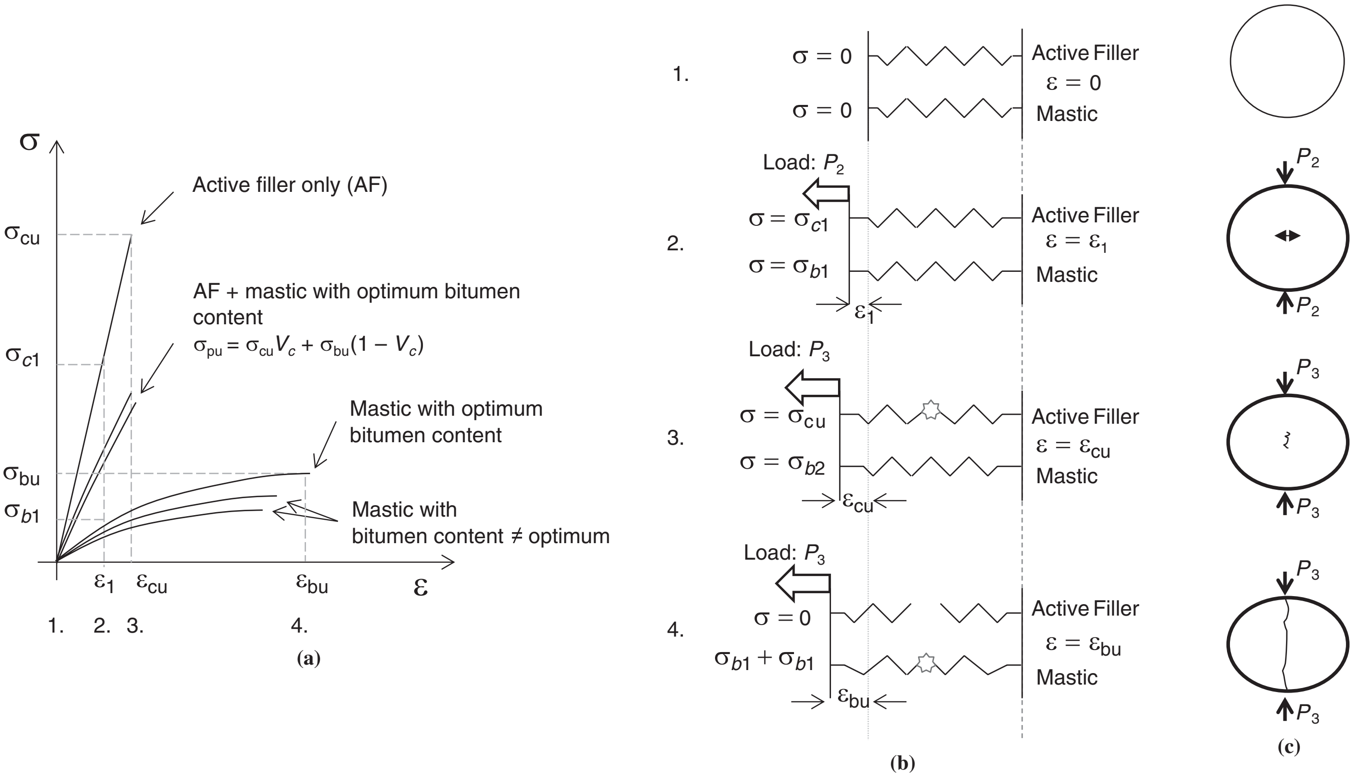
where V_c is the volume of cement in the composite. The diagram and Equation 1 explain the minimal effect of FB content compared with AF in the strength of the mixture. Since the strength or peak stress of the AF phase is much higher than that of the bitumen mastic phase, a bitumen content above or below the optimum will have comparatively little effect on the composite stress–strain curve and also on peak stress; this finding supports the results observed in the experimental work and the literature.

Interpretation of ITS Tests

The ITS test is conceptually described by using the mechanical system with unidirectional springs (Figure 7*b*) that represent the AF (cement) and the bitumen mastic (mastic) behavior in four stages:

Stage 1. With zero stress, this is the state before any load is applied.

Stage 2. The monotonic load (P) is applied and springs take a stress of σ_{c1} and σ_{b1}. Strain ε_1 is lower than fracture strain ε_{cu}.



(a) (b) (c)

FIGURE 7 Mechanical response of the composite foamed bitumen mixture: (*a*) stress–strain relationship for mixture and constituents, (*b*) conceptual mechanical system for active filler and bitumen mastic, and (*c*) ITS test.

Stage 3. P is increased up to fracture of the AF phase, and strain is ε_{cu}.

Stage 4. Since P remains constant or greater than in Stage 3, stresses from the fractured AF phase are passed to the bitumen mastic. Since σ_{cu} is much greater than bitumen σ_b, the bitumen mastic deforms rapidly up to maximum strain (ε_{bu}), and peak stress (σ_{cu}) is attained.

Interpretation of ITF Tests

In ITF tests with cyclic loading the stresses applied to AF and bitumen mastic are well below the fracture stress. For the interpretation of the fatigue test results the *S-N* or Whöler diagram is used (Figure 8), where the horizontal axis is the logarithm of the number of cycles applied (N_f) and the vertical axis is the strain applied to the composite. In the *S-N* diagram, the material behavior can be viewed as falling in three regions (*19*). Region 1 is the horizontally extending scatter band of the composite failure strain. In this region the predominant mechanism of failure is nonprogressive and represents the monotonic loading described earlier, where only one load cycle is applied. Region 2 is the fatigue life, which is governed by the progressive mechanism of cracking. In this case the AF fracture will grow followed by fracture of the bitumen mastic. Among several such cracks the one to cause failure earliest would be the one that becomes most unstable first. Region 3 is the region of no fatigue limit or endurance limit, in which fatigue cracks in the matrix are likely to develop but the stress applied is insufficient to worsen them.

The effect of different bitumen contents is also illustrated in Figure 8. At a low number of load cycles with large strains (e.g., a monotonic load), the AF and bitumen mastic will fracture with a behavior similar to that of Figure 7, and the effect of bitumen content is not necessarily clear. If the amplitude of the strain or stress applied is lower (e.g., ε_1), the composite will sustain a larger number of load cycles and cumulative damage will develop. Since the AF is brittle, fatigue microcracks will start to grow in this phase. The bitumen mastic will start gradually taking additional stress and larger strains without fracture, which in return means that the composite will sustain a larger number of load cycles. If the bitumen content is close to the optimum, the fine particles will be coated by bitumen foam, increasing the modulus, strength, and number of load cycles the mixture can withstand.

Improved Fatigue Behavior

The effect of the larger number of load cycles and a more ductile failure in FB mixtures with optimum bitumen contents observed in the experimental work has also been observed in other research projects. For example, in New Zealand a full-scale experiment was performed on pavement sections stabilized with a common 1% cement and different FB contents (*20*). Although the section with cement only (0% FB) showed a brittle failure and accelerated surface permanent deformation at the end of the full-scale experiment (after 10^6 load cycles), the sections with FB showed a lower deterioration rate and a more ductile behavior, which is consistent with the laboratory ITF test results presented in this research.

CONCLUSIONS AND RECOMMENDATIONS

It has been observed and reported in the international literature and in local mixture design of FDR mixtures with FB that ITS values do not significantly change for different FB contents when AFs are added into the mixtures; this finding makes it difficult to justify the benefits of using FB to road authorities and engineers. In this research, ITS, UCS, TrMx, and ITF laboratory tests were conducted on three representative FB mixtures. From the test results, the following conclusions are drawn:

- The ITS test results of mixtures with 1% cement and different bitumen contents were not sensitive to suggest an optimum bitumen content; this finding confirms the results found in the literature for local mixture designs.
- The dry ITS of mixtures without AF ranged between 320 kPa and 440 kPa, whereas soaked ITS ranged from 20 kPa to 80 kPa; this finding shows the importance of adding AFs to this type of FDR mixture. Some mixtures without AF did not survive the water soaking, and this shows the importance of adding AFs to these types of mixtures.

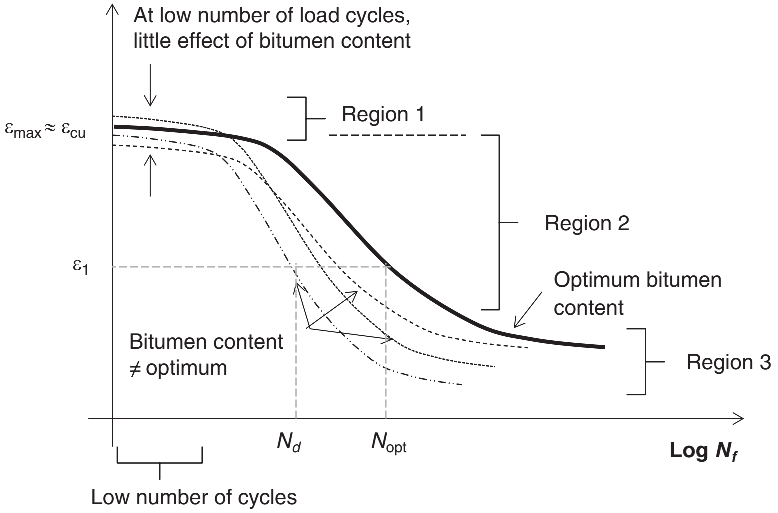


FIGURE 8 *S-N* fatigue diagram for interpretation of laboratory results.

- Different design curves were found between ITS with AF and without AF. From these results, it is not recommended to define the optimum bitumen by using the design curve without AF.
- The UCS of mixtures with 1% cement and different bitumen contents increases with increasing bitumen content. A similar trend was observed in MrTx tests.
- The mixture prepared with 2.5% bitumen content sustained the largest number of load cycles in ITF tests, doubling the mix with 1.25% bitumen content. In addition, mixtures with 2.5% bitumen content showed a more ductile failure compared with mixtures prepared with 1.25% and 3.75% bitumen content. ITF was the test most sensitive to FB content of the mixtures among all tests. In addition, a clearly different trend was observed in results from the ITS test and the ITF test, although the same type of specimens and load configuration were used.
- To explain the difference between the ITS and ITF test results, a stress–strain diagram and a simple unidirectional mechanical model were used. The model conceptually illustrates why little difference is observed in the strength of FB mixtures with AFs. In addition, an *S-N* diagram was used to explain the better performance of FB mixtures when low-amplitude stresses are applied.
- Overall, the laboratory program and material behavior interpretation indicate that when the ITS test does not provide conclusive results, the laboratory program should be complemented with ITF tests to determine the optimum FB content with more reliability. The number of load cycles to failure versus the bitumen content should be used to build design curves with more sensitivity to bitumen.

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