Comparison between Fatigue Performance of Foam Stabilized, Dense and Open Graded Asphalt Mixes

M. Saleh
University of Canterbury, Department of Civil and Natural Resources, Christchurch, New Zealand

ABSTRACT: The fatigue performance of asphalt mixes is an essential property to provide long lasting structural layers. Fatigue and permanent deformation performance are two common modes of failures that are used in most of the Mechanistic Empirical pavement design procedures. The use of foam bitumen to stabilize unbound granular materials has grown steadfastly worldwide. In this technique, about 2 to 3.0% foam bitumen together with small percentage of Portland cement about 1 to 2.0% are usually added to unbound granular materials, which will transform these materials to bound materials. Because of the high stiffness values of these mixes, they are likely to arrest high stress concentrations; therefore, fatigue cracking will be a significant form of distress in these materials. A limited experimental work to study the fatigue behaviour of the foam-stabilized mixes was carried out using the indirect fatigue test to measure the fatigue life of foam-stabilized mixes. The fatigue behaviour of both open graded porous asphalt and dense graded hot mix asphalts was also studied to provide comparison between the behaviour of these different mixes. In addition to measuring the fatigue curves of these mixes, some other parameters that are directly related to fatigue such as fracture energy and indirect tensile strength were also measured. The dense graded hot mix asphalts and the open graded porous asphalt provided longer fatigue life than foam-stabilized mixes. The fracture energy and indirect tensile strength of the dense graded hot mix asphalt was much higher than that of open graded and the foam-stabilized mixes.

KEY WORDS: Fatigue, Fracture, Energy, Foam, Asphalt

1 BACKGROUND

The use of foam bitumen to stabilize unbound granular materials has grown steadfastly as a well established technique. This stabilization when it is used with 1 or 2% cement transforms unbound materials to bound materials with high stiffness. Because of the high stiffness values for these mixes, they are likely to arrest high concentrations of tensile stresses; therefore, fatigue cracking will be a significant form of distress in these materials (Saleh, 2004).

In order to carry out Mechanistic Empirical pavement design for pavements using foam stabilized mixes, it is important to understand the possible modes of failures of these materials and establish reliable performance transfer functions. In this research, a comparison between the fatigue performance of foam stabilized mixes, open graded friction course and hot mix asphalt dense graded mixes was carried out.

2 SAMPLES PREPARATIONS

2.1 Aggregate Gradations and mix compositions for Foam Asphalt Mixes

Two aggregate gradations were used, which are the upper limit of the gradation band of the AP-40 (all passing the 40 mm sieve) and the mid-point of AP-20 gradation curve. These two gradations were selected because they are reasonably close to the mid-point of the ideal zone for foamed bitumen mixes; this was discussed in previous study by the author (Saleh & Herrington, 2003 and Saleh,. 2006). In addition, four types of mineral filler: fly ash type C, Huntly pond ash, hydrated lime, and Portland cement, were used to adjust the amount of fines. The Portland cement was used at 1.0% and 2.0% with fly ash type C. Huntly pond ash is a by-product of power generation boilers, and can cause an environmental hazard because of its alkalinity, high concentrations of boron, and presence of several heavy metals such as arsenic and cadmium. Using it in foam stabilization was investigated as a potential safe way of discarding it economically. The optimum foam and water contents were determined so that the resilient modulus of the mixture is maximized. The optimum foam and water contents varied according to the aggregate gradation and the type of mineral fillers.

Table 1 shows the different combinations of AP-40, AP-20, and the mineral fillers that have been investigated. The name of each group has been designated with letters and numbers to indicate the aggregate gradation, the types of filler, and the percentage of Portland cement, if any. For example, M20FA indicates that the mix contains AP-20 gradation with fly ash as a mineral filler, while M20FA2C is a mix containing AP-20 gradation, fly ash, and 2.0% Portland cement.

The 150-mm diameter specimens were prepared in accordance with AS 2891.2.2, 1986, using AP-40 aggregate, 80 gyration cycles, and a 3^{o} gyratory angle. The 100-mm-diameter specimens were prepared using AP-20 aggregate, 80 gyration cycles, 240 kPa air pressure, and 2^{o} gyratory angle. The 150-mm-diameter mould was used for the AP-40 aggregates and the 100-mm-diameter mould was used for the AP-20 aggregates.

Table 1: Names designated to foam-stabilized mixes based on their compositions.

Aggregate Gradation	Type of Mineral Filler				
	Fly Ash Type C (FA)	Fly Ash C + 2.0% Cement (FA2C)	Fly Ash C + 1.0% Cement (FA1C)	Huntly Pond Ash (PA)	Hydrated Lime (LM)
AP-20	M20FA	M20FA2C	M20FA1C	M20PA	M20LM
AP-40	N/A	N/A	N/A	M40PA	M40LM

2.2 Mixing, Compaction and Curing

The dry aggregate was mixed with water at optimum mixing moisture content, and then mixed with the optimum foam content, and subsequently compacted using the Gyropac compactor. Curing took place at room temperature for seven days and the mixtures were then oven-dried until a constant weight was achieved. Both the dense graded, AC10 HMA, and the open graded porous asphalts, OGPA, were taken from a local supplier in Christchurch. The AC10 HMA is general purpose wearing course of maximum nominal size 10 mm.

3 INDIRECT TENSILE FATIGUE TEST

The Nottingham indirect fatigue test was used to measure the fatigue life of foam-stabilized mixes (Read & Brown 1996). In this test, the specimen is loaded diametrically with a vertical compressive force as shown in Figure 1. This indirectly generates a tensile stress across the vertical diameter. For any stress level specified by the operator, the magnitude of the applied compressive force and the corresponding horizontal tensile strain can be calculated by the following equations.

$$P = \frac{\sigma_{x\max} * \pi * d * t}{2} \tag{1}$$

$$\varepsilon_{x\max} = \frac{\sigma_{x\max}}{E} * (1 + 3 * \nu) * 1000 \tag{2}$$

where:

P = Vertical compressive force (kN)
$\sigma_{x\max}$ = Maximum horizontal tensile stress (kPa)
$\varepsilon_{x\max}$ = Maximum horizontal tensile strain (με)
ν = Poisson's ratio
d = Diameter of the specimen (m)
t = Thickness of the specimen (m)
E = Indirect resilient modulus of the specimen (MPa)

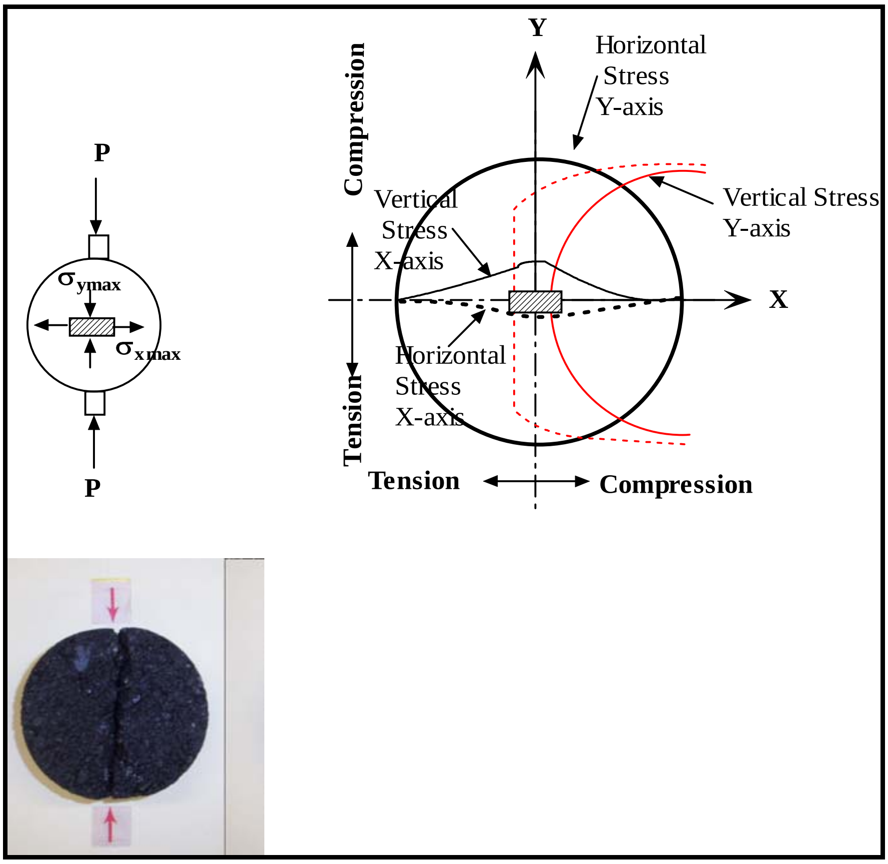

Figure 1: Stress distribution in the indirect tensile fatigue test (ITFT) loading.

4 FATIGUE MODELS

In order to develop a fatigue relationship for foam stabilized mixes, dense graded and open graded porous hot mix asphalts, a number of identical specimens were prepared. The indirect resilient modulus values of these specimens were tested. The horizontal tensile strain developed at the centre of the test specimen during the fatigue test can be calculated from Equations 1 and 2 for any applied load.. The size of the test specimen is important because the value of the applied stress (σ_{xmax}) and therefore the generated horizontal tensile strain is dependent upon it.

The preferred geometry for the indirect tensile fatigue test (ITFT) is a 100 mm-diameter and 40 mm-thick specimen (Read & Brown 1996). With such dimensions, to generate a horizontal tensile stress of 600 kPa, a force of about 4.3 kN has to be applied on the specimen. This is within the capacity of the loading frame (about 5 kN) of the Universal Testing Machine, UTM, available at the University of Canterbury.

The failure is defined to have occurred when either of the following two cases occurs first:

1. A direct split of the specimen, or
2. The vertical deformation reaches 9 mm, as defined by Read & Brown (1996).

To obtain a fatigue life curve, the normal procedure is to test the first specimen at the maximum achievable horizontal stress level, and then test the subsequent specimens at lower stress levels. Once all testing is complete, the horizontal tensile strain generated at the centre of the specimens is calculated from Equation 2. The initial horizontal tensile strain is then plotted versus the number of load repetitions to failure on a log-log graph and the nonlinear regression is used to developed the relationship between the number of load cycles to failure and the applied initial strain and other mix properties such as resilient modulus. This relationship can then be compared with fatigue relationships of known materials to evaluate the relative performance.

In this research, the indirect tensile fatigue test was carried out on dense-graded Hot Mix Asphalt with a maximum nominal size of 10 mm, AC10 HMA, open-graded porous asphalt (OGPA), and foam-stabilized mix (M20FA1C). Two sets of fatigue models were developed for the three mixes used, and are shown by equations 3 and 4.

$$N_f = a * \varepsilon^b \tag{3}$$

$$N_f = \alpha * \varepsilon^\beta * M_r^\gamma \tag{4}$$

where:

N_f = Number of load repetitions to failure

ε = Initial horizontal tensile strain in mm/mm

M_r = Resilient modulus in MPa

a, b, α, β, and γ = regression constants depending on the material type

4.1 Fatigue Models for AC10 Dense-Graded HMA

Equations 5 and 6 are the fatigue equations developed for dense-graded HMA at the University of Canterbury Transportation Laboratory. Figures 2 compares the predicted and measured numbers of load repetitions for the fatigue model represented by Equation 5. The coefficient of determination (R^2) for both models is very close to 1 (one), which means that these models explain at least 99% of the variability of the data. Although Equation 6 explicitly accounts for the effect of the resilient modulus, Equation 5 however implicitly accounts for the effect of the modulus because the modulus value will affect the resulted tensile strains.

$$N_f = 2.35*10^{-13}*\varepsilon^{-4.719} \qquad R^2 = 0.996 \qquad (5)$$

$$N_f = 6.64*10^{-11}*\varepsilon^{-4.5144}*M_r^{-0.5116} \qquad R^2 = 0.995 \qquad (6)$$

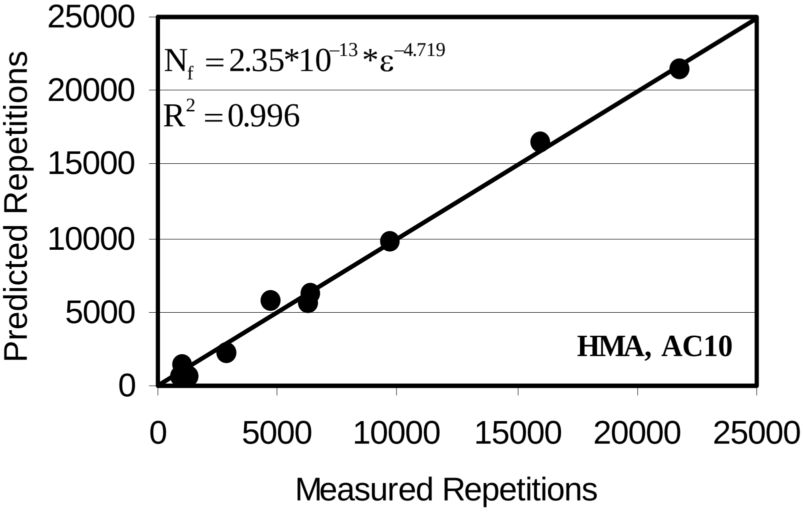

Figure 2: Predicted versus measured number of load repetitions for fatigue models for AC10 HMA using equation 5 model

Figure 3 shows a comparison between the University of Canterbury (UC) fatigue model and BRRC (Belgian Road Research Centre), TRRL (Transport Road Research Laboratory, UK), PDMAP (Probabilistic Distress Model for Asphalt Pavement, USA), and the Shell fatigue model. It should be noted that the BRRC, TRRL were calibrated for field conditions. In other words, these models have been shifted by using shift factors to adjust the laboratory models to match the field performance. The fatigue curves shown for Shell and the PDMAP are both laboratory developed fatigue models without any field calibrations. The UC model is reasonably close to both BRRC and PDMAP fatigue models.

The difference among the three models could be related to the difference in the materials tested or the laboratory test method. There is a shift factor of up to 30 between the TRRL fatigue model and the UC model, and of up to 100 between the Shell and UC models. This is due to field calibration adjustment and probably to the difference in the material properties and the test conditions. The UC fatigue model for dense-graded HMA needs field calibration to adjust it to New Zealand field conditions. It should be noted that stress controlled test was used to develop UC models, however, some other models such as Shell used strain controlled tests. A close look to Figure 3 clearly shows the significant difference between the fatigue life predicted by the different models, therefore New Zealand should develop its own fatigue models that cover a wide range of materials for different types of binders (polymer modified or conventional binders) which suit its materials, climate, and traffic loading.

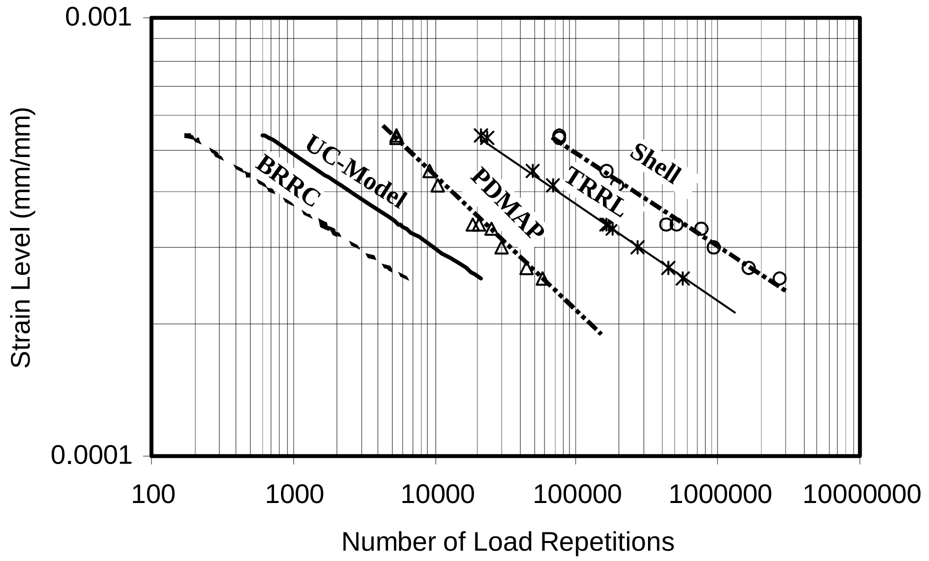

Figure 3: Comparison between University of Canterbury fatigue model (UC-Model) and other fatigue models for HMA.

4.2 Fatigue Models for Open-Graded Porous Asphalt (OGPA)

Equations 7 and 8 show the fatigue models developed for open-graded porous asphalt (OGPA). Figure 4 show the measured versus predicted number of load repetitions for both models shown by Equations 7 and 8. Both models reasonably predict the number of load repetitions to failure.

$$N_f = 6.31 * 10^{-5} * \varepsilon^{-2.18143}$$
$$R^2 = 0.93 \qquad (7)$$

$$N_f = 1.21 * 10^{-9} * \varepsilon^{-2.56} * M_r^{1.0704}$$
$$R^2 = 0.903 \qquad (8)$$

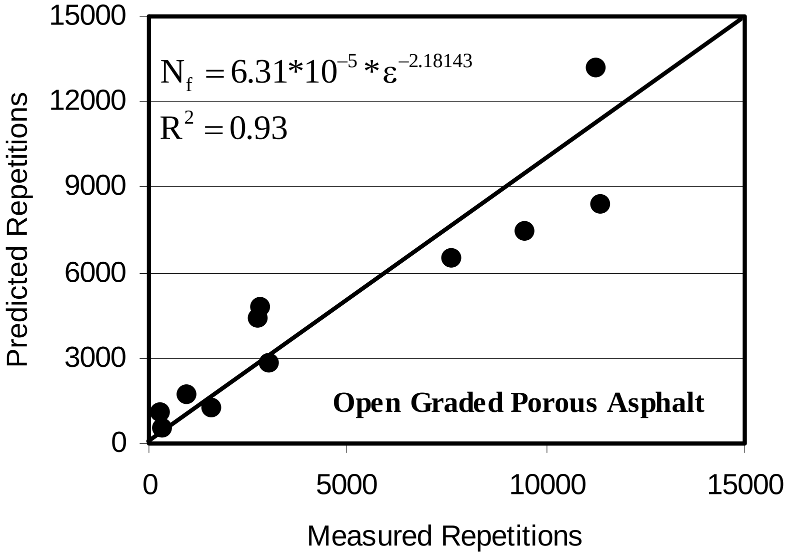

Figure 4: Predicted versus measured number of load repetitions for open-graded porous asphalt using equation 7 model

4.3 Fatigue Models for Foamed Bitumen-Stabilized Mixes

Equations 9 and 10 are the two forms of fatigue models developed for M20FA1C mixes. Figure 5 illustrates the goodness of fit of the model shown in Equation 10. Figure 6 shows a comparison between the fatigue life of AC10 HMA, open-graded porous asphalt (OGPA) and foam-stabilized mix M20FA1C. It is obvious that HMA has a much higher fatigue life compared to foam-stabilized mixes when they are compared at the same tensile strain level. The high fatigue life of the HMA can be attributed to the high binder content, and the good homogeneous coating of bitumen on all aggregate particles that provide flexibility to the mix.

In Figure 6, the slopes of the fatigue curves of the OGPA and the foam-stabilized mixes are steeper than that of the HMA. This clearly indicates that the fatigue performance of these mixes is inferior to that of the HMA mixes.

$$\begin{aligned} N_f &= 7.67*10^{-3}*\varepsilon^{-1.2207} \\ R^2 &= 0.979 \end{aligned} \tag{9}$$

$$\begin{aligned} N_f &= 0.3208*\varepsilon^{-2.525}*M_r^{-1.9256} \\ R^2 &= 0.996 \end{aligned} \tag{10}$$

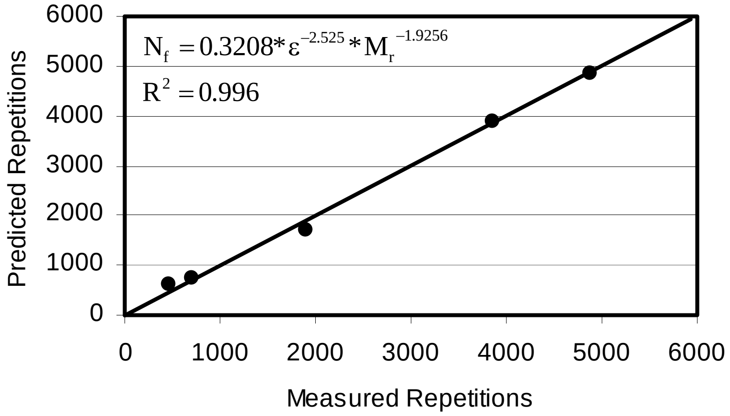

Figure 6: Predicted versus measured number of load repetitions for foam-stabilised mix using equation 10 model.

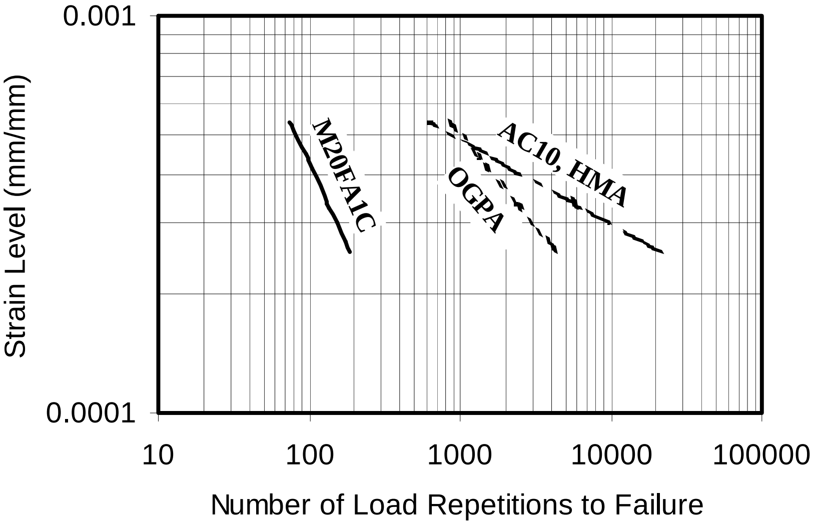

Figure 7: Fatigue life for the 3 different types of mixes M20FA1C, OGPA, and AC10 HMA

4.4 Indirect Tensile Strength (ITS) and Fracture Energy

The ITS was determined in accordance with NZS3112:Part 2:1986 with a loading speed of 50.8 mm/min. The specimens were placed in the loading frame and aligned to ensure that the axis of symmetry and direction of loading act through the centroid of the specimens. The ITS of the mixtures was obtained using the following equation.

$$ITS = \sigma_{x\max} = \frac{2 * P_{\max}}{\pi * d * t} \times 1000 \qquad (11)$$

where:

ITS = indirect tensile strength (kPa)

σ_{xmax} = maximum horizontal tensile stress (kPa)
P_{max} = maximum applied force or load (N)
d = diameter (mm)
t = specimen height (mm)

The indirect load and the corresponding vertical deformations were recorded. The fracture energy of foam-stabilized mixes was computed by calculating the area under the force displacement curve between zero load and peak load at failure. The effect of gradation and type of mineral fillers on the ITS and fracture energy was quite clear from the test results shown in Table 2. Foam-stabilized mixes with Huntly pond ash as a mineral filler (M20PA and M40PA) showed the lowest ITS value while those containing fly ash type C and fly ash type C with 1% or 2% cement showed a significant increase in ITS values.

Table 2: Indirect Tensile Strength (ITS) of the foam-stabilized mixes and AC10 HMA.

Mix type	Indirect Tensile Strength, ITS (kPa)
M20LM	142
M20PA	72
M40LM	153.5
M40PA	63
M20FA	359
M20FA1C	378
M20FA2C	388
AC10 HMA	1198

The ITS value for the AC10 HMA is about 3 times the highest ITS value for foam-stabilized mixes. It was also clear from the results that the fracture energy of the HMA is much higher than that of the foam-stabilized mixes. In addition, the AC10 HMA shows much more flexibility than the foam-stabilized mixes since the amount of deformation before failure for the HMA is much higher than that for the foam-stabilized mix. This difference in ITS and fracture energy values between HMA and foam stabilized mixes can be attributed to the higher binder content in the HMA compared to that in the foam-stabilized mixes. This significant difference in the values of the indirect tensile strength and fracture energy agrees with the fatigue test results discussed in the previous section.

5 CONCLUSIONS

The fatigue behaviour of the foam-stabilized mixes was investigated, as well as that of dense-graded AC10 HMA and open-graded porous asphalt (OGPA), to compare their fatigue life performance. Foam-stabilized mixes provided a lower fatigue life compared to HMA and OGPA. The fatigue models developed in this study should only be used for purposes of comparison. These fatigue models were developed using the indirect tensile fatigue test with constant stress mode and only one replicate for each stress level was made. In order to get more reliable fatigue models, with which to determine the actual fatigue life, a more comprehensive testing programme is required to use different test methods such as beam fatigue, and other modes of testing such as constant strain test.

The indirect tensile strength test (ITS) and fracture energy were carried out for different foam-stabilized mixes and was compared with that for HMA. HMA provided higher ITS and fracture energy values compared to foam-stabilized mixes. The effects of gradation and the type of mineral fillers were quite noticeable, as active fillers such as fly ash type C and Portland cement noticeably improved the ITS and fracture energy values for foam-stabilized mixes.

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