International Journal of Transportation Science and Technology 8 (2019) 263–279

Contents lists available at ScienceDirect

International Journal of Transportation Science and Technology

journal homepage: www.elsevier.com/locate/ijtst

Determination of endurance limit for different bound materials used in pavements: A review

Brundaban Beriha [a], Umesh C. Sahoo [a,*], Wynand JvdM Steyn [b]

[a] School of Infrastructure, Indian Institute of Technology Bhubaneswar, India
[b] Department of Civil Engineering, University of Pretoria, South Africa

ARTICLE INFO

Article history:
Received 31 December 2018
Received in revised form 22 March 2019
Accepted 1 May 2019
Available online 9 May 2019

Keywords:
Bound material
Endurance limit
Perpetual pavement

ABSTRACT

Perpetual pavements are in existence since 1960 with satisfactory performance. These pavements are usually designed based on the endurance limit property of bound pavement materials, which is the critical stress or strain, below which the material can be subjected to an infinite number of load repetitions without causing fatigue failure. The endurance limit value significantly affects the design of a perpetual pavement. Various methods have been proposed for determination of endurance limits for different types of bound pavement materials. This paper presents a comprehensive review of such methods and suggests the suitable method to be adopted for the determination of endurance limit based on bound material type after critical discussions.

1. Introduction

Rapid growth in traffic, material scarcity and environmental concerns are compelling future road designs to be economical, sustainable and maintenance free (Ferne, 2006). A long-life asphalt pavement or perpetual pavement meets these criteria. By definition, any pavement lasting more than 40 years without requiring structural rehabilitation is termed a perpetual pavement (APA, 2002). A perpetual pavement can thus sustain all the traffic load expected on it for a period of 40 years without failing structurally.

Perpetual pavements are in use since 1960 (Newcomb et al., 2001) in countries like the United States of America (USA) and United Kingdom (UK). Experiences from the European countries have also shown that fully flexible pavement and semi-rigid pavement can be used as long life pavements (Ferne, 2006). The key idea of designing perpetual pavements is to eliminate the two most common structural failure conditions of pavements i.e. fatigue cracking and rutting. Fatigue cracking is generally associated with layers having bound materials, while rutting is associated with both bound and unbound materials. The commonly used bound materials are bituminous mix, concrete, cement stabilized material, etc. The mechanistic parameter which governs the fatigue cracking of a bound layer is the tensile strain at a specific critical location (mostly the bottom) of the layer. When the tensile strain at the critical location is kept below a threshold value, the fatigue life of that layer approaches infinity.

Peer review under responsibility of Tongji University and Tongji University Press.
* Corresponding author.
E-mail address: ucsahoo@iitbbs.ac.in (U.C. Sahoo).

https://doi.org/10.1016/j.ijtst.2019.05.002
2046-0430/

Laboratory fatigue studies (Monismith, 1992; Ramakrishnan et al., 1989; Aramoon, 2014; Jitsangiam et al., 2016) and field studies (Nunn et al., 1997; Nishizawa et al., 1997; Wu et al., 2004) confirmed the existence of an endurance limit for different bound materials. These studies reported a wide range of endurance limit values (even for the same type of bound material), which suggests that the endurance limit value is material specific and cannot be generalized. Another study by Witczak et al. (2013) reported that the endurance limit value is dependent on the testing mode and conditions. As the endurance limit value plays a critical role in designing a perpetual pavement, it should be chosen rationally. Hence, an extensive literature review was undertaken to compare different methodologies adopted to determine the endurance limit of different bound materials and to obtain suitable approaches for each specific bound material. The bound materials considered in this paper are bituminous mix and hydraulically bound materials which include concrete and other stabilized materials.

2. Endurance limit (EL)

During the design life, most of the pavement structures do not experience the ultimate or failure load but is subjected to cyclic loads with magnitudes much less than the ultimate load. The cyclic loading and unloading process gradually weakens the material resulting in failure. This phenomenon is called fatigue. The repeated loading and unloading process generates microscopic cracks in the material which later coalescence to form macro cracks leading to fracture of the material. The entire fatigue life can be divided into three phases (Mazars, 1986, Bateman, 2012); Phase I- generation of micro cracks, Phase II-coalescence of micro cracks to form macro cracks and Phase III-rapid crack propagation to cause failure. Out of the three phases, phase II covers the majority of the fatigue life.

The number of load cycles to fatigue failure (known as fatigue life N_f) shows an inverse relationship with the applied load level or stress level (S). The curve of log N_f vs S depicts a linear relationship between the variables, first reported by Wöhler (1860) for metals and therefore known as Wöhler S/N curve (Fig. 1). This relationship holds true up to a certain stress level below which the fatigue life tends towards infinity making the S/N curve flat. This stress level is termed as the endurance limit at which the material can be subjected to an infinite number of load repetitions without failure. This marked the inception of the concept of endurance limit, later observed in many other materials.

3. Methods for determination of endurance limit of different bound pavement materials

The existence of the endurance limit provides an infinite or indeterminable fatigue life to the materials. As it is impossible to test materials for infinite cycles, researchers adopt different threshold testing criteria, which rationally supports the existence of the endurance limit. A comprehensive review of the different methodologies used for determination of endurance limit of bound materials is provided in the following sections.

3.1. Bituminous mix

3.1.1. Convergence method

Monismith and McLean (1972) observed that for bituminous mixes the log–log relationship between strain and the loading cycle converges at 5 million cycles at a strain value of 70 $\mu\varepsilon$ (Fig. 2). They proposed this strain value as the endurance limit. The convergence shows that irrespective of the modulus value, all the bituminous mixes would have fatigue life in excess of 5 million cycles, when the strain value is less than 70 $\mu\varepsilon$. The fatigue behavior of bituminous mixes at low strain level is different from that of high strain level. They proposed this strain value as the endurance limit. Similar convergence was reported by Maupin and Freeman (1976).

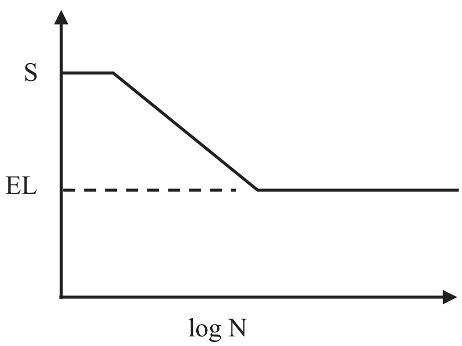

Fig. 1. Typical Wöhler S/N Curve.

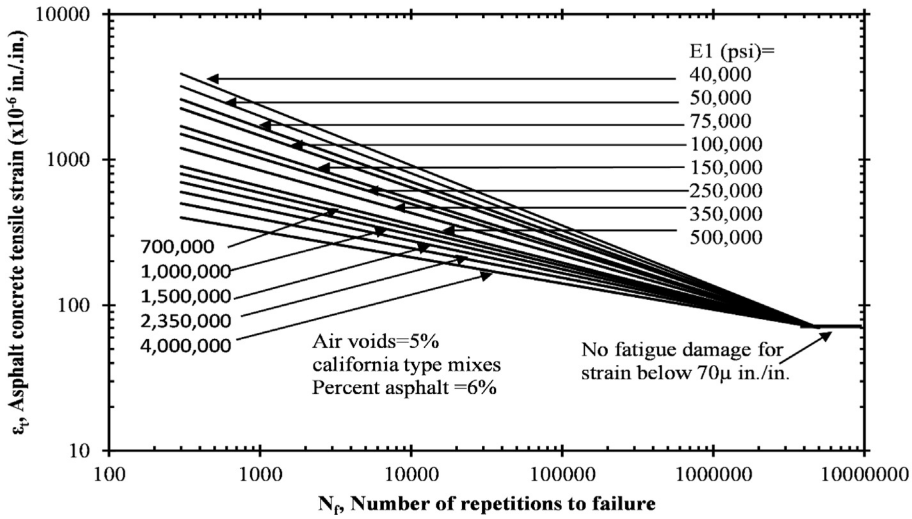

Fig. 2. Bituminous Mixes Fatigue Curve (Monismith and McLean 1972).

3.1.2. Extrapolation of fatigue life

As per the definition, endurance limit represents a stress/strain level which results in an infinite life, but practically it is impossible to test any material for infinite life. Therefore, a practical threshold fatigue life should be set, which would be long enough to justify the endurance limit concept. For perpetual pavement application, APA (2002) suggests a threshold fatigue life of 40 years for pavement materials. Based on the estimation by Prowell et al. (2010), approximately 500 million standard axles (MSA) loads can be expected on the pavement over a period of 40 years (long life). The Strategic Highway Research Program (SHRP) suggests that for bituminous mixes, a laboratory fatigue life of 50 million load cycles in a strain controlled test is equivalent to 500 MSA in the field, considering a shift factor of 10 (Leahy et al., 1995). Therefore, any strain value which can result in a laboratory fatigue life of 50 million can be considered as an endurance limit. The laboratory fatigue life of bituminous mixes refers to the load cycle corresponding to a 50% reduction of the initial modulus. The test is conducted in a strain controlled mode at a frequency of 10 Hz. Conducting laboratory fatigue test for 50 million cycles at the standard testing frequency of 10 Hz would take more than 50 days for a single sample which is impractical for routine determination of endurance limit. Hence, different extrapolation techniques such as the exponential model (AASHTO T321), power model (Shen and Carpenter, 2005), logarithmic model (Prowell and Brown, 2006), single-stage Weibull function (Tsai et al., 2002), and three-stage Weibull function (Tsai et al., 2005) have been used to predict high fatigue lives at low strain level from the data obtained from higher strain level testing, which is relatively less time consuming. Figs. 3–5 show different extrapolation techniques being used to predict fatigue lives.

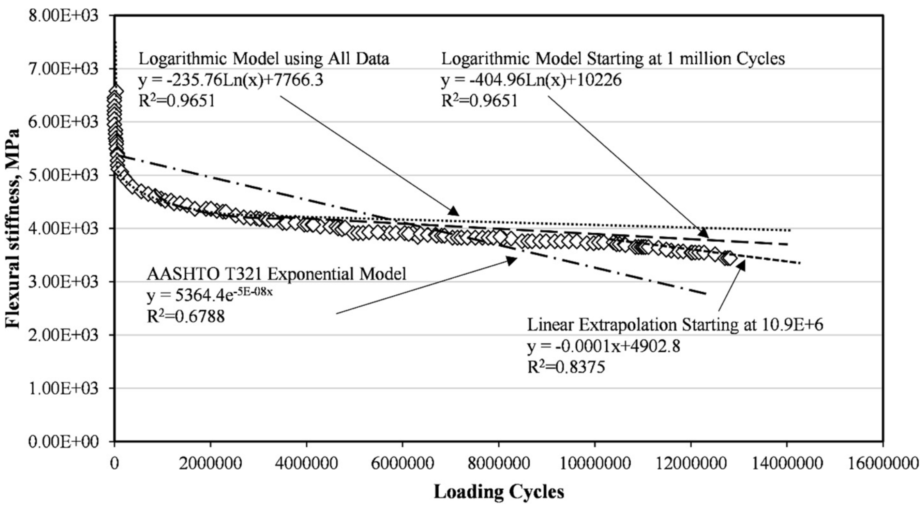

Fig. 3. Four methods of extrapolation using one data set (Prowell and Brown 2006).

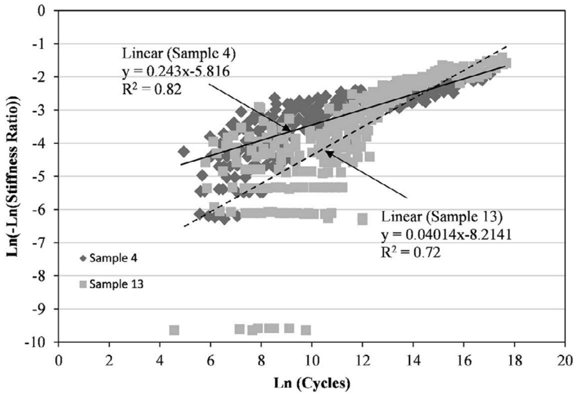

Fig. 4. Single stage Weibull Extrapolation (Prowell et al., 2010).

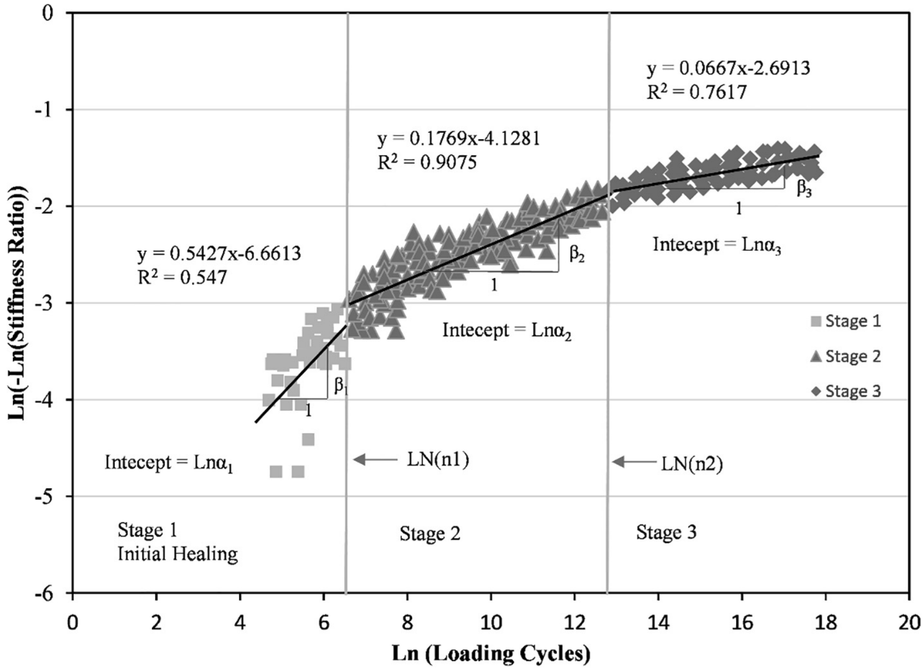

Fig. 5. Three stage Weibull Extrapolation (Prowell et al., 2010).

3.1.3. Ratio of dissipated energy change (RDEC) approach

Shen and Carpenter (2005) observed that the change in dissipated energy during fatigue testing could be used to predict the fatigue life of bituminous mixtures. Dissipated energy is the amount of energy lost due to damage induced in the material during the loading and unloading process. They expressed the damage in terms of the ratio of dissipated energy change (RDEC) shown in Eq. (1).

$$RDEC = \frac{DE_{n+1} - DE_n}{DE_n} \tag{1}$$

where

RDEC = ratio of dissipated energy change
DE_n = dissipated energy produced in load cycle n
DE_{n+1} = dissipated energy produced in load cycle n + 1

A plot of RDEC vs loading cycles (Fig. 6) shows that the RDEC value decreases rapidly for the first few cycles and then remains almost constant for a period where a consistent amount of dissipated energy is attributed to generating micro

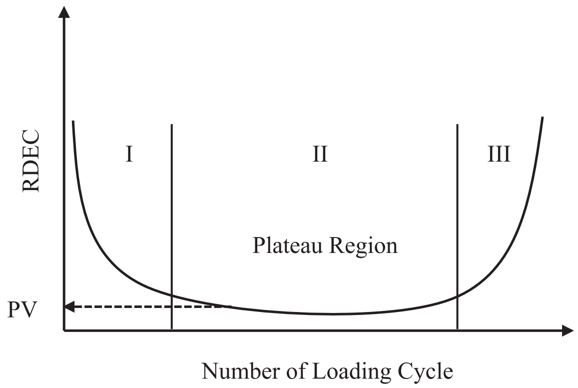

Fig. 6. Typical RDEC versus loading cycles plot and the indication of PV.

cracks. The RDEC value during this period (plateau region) is termed the plateau value (PV). The micro cracks coalesce to form bigger cracks, leading to failure during which the RDEC value increases suddenly. The point that marks the sudden increase in the RDEC signifies fatigue failure.

The PV and N_f (cycle corresponding to 50% modulus reduction) follows a unique relationship (Fig. 7) irrespective of mixture types, loading modes, frequency, and rest periods. The relationship even holds true for low strain fatigue testing which could be used to find the endurance limit. Fatigue test can be carried out for 500,000 load cycles (LC), followed by a plot of the RDEC-LC data to generate the unique PV-N_f curve. The LC corresponding to the intersection point is the fatigue life. HMA mixtures with PV below 6.74e-09 was found to have very long fatigue lives. Therefore a PV of 6.74e-09 was suggested as the threshold value for endurance limit behavior. Carpenter et al. (2003) recommended to use an advanced strain measuring device for more accurate measurement of dissipated energy at low strain levels and to also reduce the chances of creep due to measurement over a long time.

The RDEC approach does not consider the effect of rest period in its formulation. Underwood and Kim (2009) noticed this drawback and suggested to update the PV depending upon the rest period using Eq. (2).

$$PV = PV_0(RP + 1)^a \tag{2}$$

where

PV_0 = plateau value under continuous loading for the given strain amplitude and temperature for the mixture of interest
RP = rest period
a = mixture-dependent coefficient.

3.1.4. Healing approach

Many researchers (Carpenter et al., 2003; Bhattacharjee et al., 2009; Souliman, 2012; Witczak et al., 2013) observed that during fatigue testing of bituminous materials at low strain levels, the damage behavior is significantly different compared to

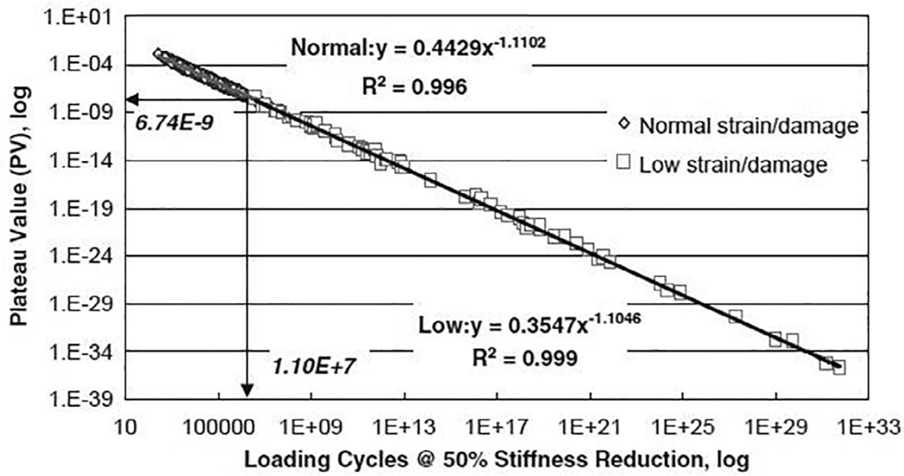

Fig. 7. PV-Nf relationship (Shen and Carpenter, 2005).

normal strain level testing attributed to a healing process. Healing is the capability of a material to self-recover its mechanical properties (stiffness or strength) lost due to damage during the loading process. It occurs during the unloading/ rest period. The existence of an endurance limit in HMA is a result of the change in the damage behavior which could not be explained with traditional fatigue analysis but rather needs a different approach. Souliman (2012) and Witczak et al. (2013) correlated damage to healing phenomenon for both beam fatigue and uniaxial fatigue tests to find endurance limits for HMA mixes. The healing approach may broadly be divided into Healing Index method and Stress Stiffness method.

3.1.4.1. Healing index (HI) method. In an HMA fatigue test, the damage is monitored in the form of change in stiffness ratio (SR) which is the ratio between the stiffness at any given cycle and the stiffness at the 50th cycle. For a typical test, the SR value starts with 1 and gradually decreases to a value of 0.5 (failure criterion). The rate at which it will decrease depends on the HMA mixture properties and rest period. A typical curve of SR vs number of cycles, with and without rest period is shown in Fig. 8.

In Fig. 8, the difference between the curves shows the effect of healing. A test at the endurance limit results in a horizontal line indicating complete healing of damage caused during loading. Souliman (2012) developed a parameter called the Healing Index (HI), which is defined as the difference between the stiffness ratios (SR) for the tests with and without a rest period at N^* (number of cycles to failure for the test without rest period) given in Eq. (3).

$$HI = [SR_a - SR_b]_{at} N^* \tag{3}$$

where

SR_a = stiffness ratio with rest period
SR_b = stiffness ratio without rest period

To find the endurance limit, all HI vs strain data are plotted (Fig. 9) for different temperatures and rest periods as it is expected to have an effect on the endurance limit value. The strain value corresponding to a HI value of 0.5 is considered as the endurance limit for that temperature and rest period. At an HI value of 0.5, SR_a = 1.0 and SR_b = 0.5.

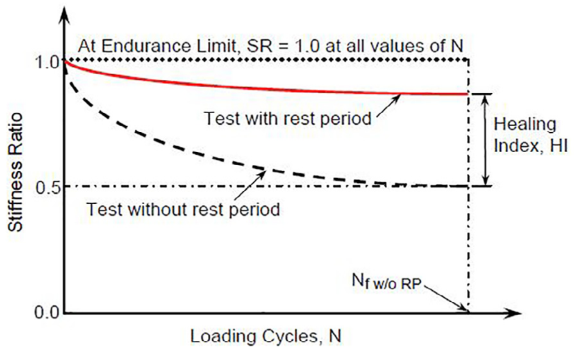

Fig. 8. Typical SR vs No. of load cycles for tests with and without rest period (Witczak et al., 2013).

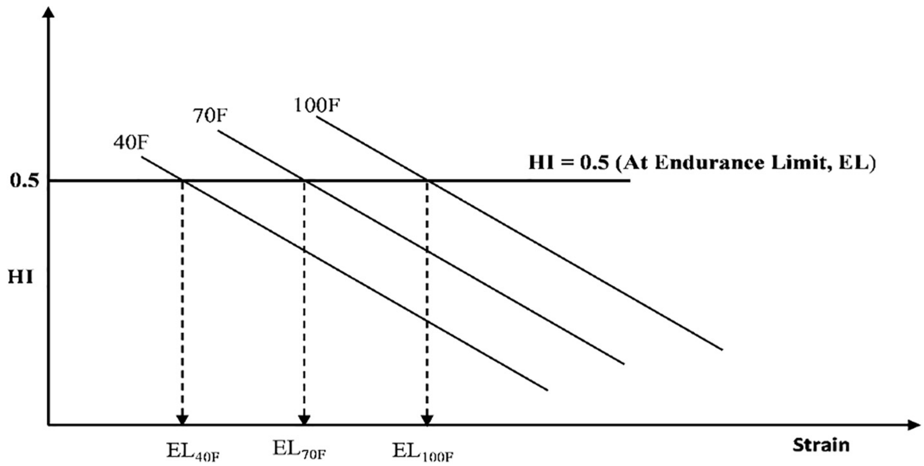

Fig. 9. Endurance limit determination at different temperatures based on HI (Souliman, 2012).

Witczak et al. (2013) applied the same healing concept adopted in a beam fatigue test to uniaxial (tension–compression) fatigue test. They replaced the stiffness parameter with a pseudo-stiffness to separate healing due to viscoelastic property of mixture. To study the effect of healing due to the rest period, two parameters were introduced. The first parameter is called the healing ratio difference (HRD) which is the arithmetic difference between the pseudo stiffness ratios with and without the rest period measured at any number of cycles (given by Eq. (4)). The second one is termed the healing index (HI) which is different from the HI parameter used in the beam fatigue test and defined as the healing ratio difference divided by the full healing (1- PSR_b) given by Eq. (5).

$$HRD = [PSR_a - PSR_b] \tag{4}$$

$$HI = \frac{(PSR_a - PSR_b)}{(1 - PSR_b)} \tag{5}$$

where

PSR_a = Pseudo stiffness ratio with rest period at loading cycle N
PSR_b = Pseudo stiffness ratio without rest period at the same N

To determine the endurance limit, a regression model was developed to correlate PSR with factors like binder content, air voids, rest period and tensile strain. The HI value is calculated using Eq. (5), where the desired PSR values are obtained from the regression model by inserting a suitable value. The HI values are plotted against tensile strain values for different temperature and mixture conditions. The strain value corresponding to the HI value of 1.0 is considered as the endurance limit, where complete healing happens in the rest period. This method can be used without using a PSR regression equation, but the sample needs to be tested at a minimum of two different strain levels with and without a rest period at a constant temperature. The HRD is plotted against the strain value and the strain value at HRD = 0.5 is the endurance limit.

3.1.4.2. Stiffness ratio (SR) method. In this method, a regression equation as described in Eq. (6) is developed to correlate SR with different mixture properties (binder content, air void, etc.), testing parameters (strain, rest period) and loading cycle. The strain value corresponding to an SR value of 1 (keeping all other parameters constant) is considered as the endurance limit. Witczak et al. (2013) suggested that setting the SR value to 1 is a better approach than setting the HI to 0.5, as the SR approach can be used for any number of load repetitions (N), but the HI approach can be used at N^* only. Also, this method has an advantage over the HI method as it can be used to find the endurance limit for the continuous test conditions.

$$SR = f(BG, AC, V_a, T, \varepsilon, N, RP) \tag{6}$$

where

BG is the binder grade, AC is the binder content, Va is the air voids, T is the temperature, ε is the initial strain, N is the number of load applications, RP is the rest period between load applications.

Similarly, for uniaxial fatigue tests, the regression equation is developed for PSR rather than SR. Fig. 10 indicates that for a particular rest period and N, the PSR value decreases as the strain value increases. Thus the endurance limit is defined as the strain level for which PSR = 1.0 (Witczak et al., 2013).

Singh et al. (2016) observed that the fatigue data obtained from 4 point bending beam testing is specimen dependent i.e., the result would vary with specimen geometry, whereas fatigue data derived from uniaxial testing truly represents material characteristic rather than specimen property.

3.1.5. Continuum damage modeling

3.1.5.1. Simplified viscoelastic continuum damage (S-VECD) modeling. The S-VECD analysis of fatigue data involves in developing a constitutive model to find the relationship between stress and strain. To develop a simple linear elastic type equation, the model replaces strain with pseudo-strain using the elastic–viscoelastic correspondence principle (Underwood et al., 2010). The physical strain is converted to pseudo-strain through a convolution integral as given in Eq. (7). The model tracks the development of micro damage (S) during fatigue testing through the reduction in pseudo-stiffness (C) (stress/pseudo strain). The relationship between stress, pseudo-strain and internal damage is obtained using work potential theory as given in Eq. (8).

$$\varepsilon^R = \frac{1}{E_R}\int_0^t E(t-\tau)\frac{d\varepsilon}{d\tau}d\tau \tag{7}$$

where

ε^R = pseudo strain
ε = physical strain

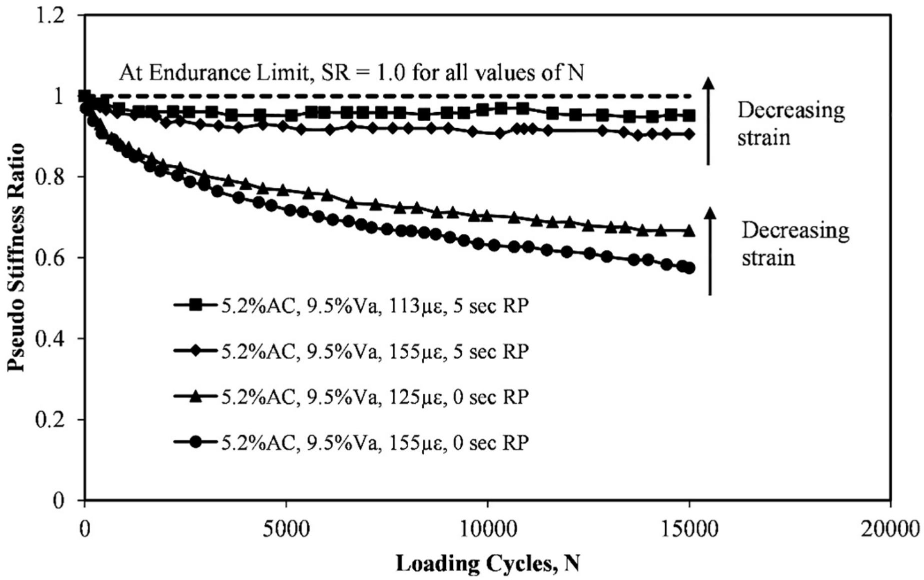

Fig. 10. Effect of strain and rest period of PSR as a function of the loading cycles (Witczak et al., 2013).

E(t) = LVE relaxation modulus
τ = integration term
t = time
E_R = reference modulus (taken as 1)

$$\frac{dS}{dt} = \left(-\frac{\partial W^R}{\partial S}\right)^{\alpha} = \left(-\frac{1}{2}(\varepsilon^R)^2\frac{dC}{dS}\right)^{\alpha} \tag{8}$$

where

$$WR = \text{pseudo - strain energy density function} = \frac{1}{2}(\varepsilon^R)^2 C$$

The relationship between C and S is unique and known as the damage characteristic curve (Fig. 11), which is independent of loading mode, loading rate, and stress/strain amplitude and temperature (Underwood et al., 2010) as long as the material is restricted to its elastic and viscoelastic behavior. In this approach, once the damage characteristic curve is developed which generally takes the form of a power law (Eq. (9)) or an exponential form (Eq. (10)), a closed-form solution is developed to predict the number of cycles to failure for a given strain input through different modes of loading. A fatigue life prediction model developed by Hou et al. (2010) for controlled-strain direct tension cycle test with a power law damage model is given by Eq. (11). The endurance limit can be obtained by solving Eq. (11) for a strain value that results in an N_f value of 50 million.

$$C(S) = e^{aS^b} \tag{9}$$

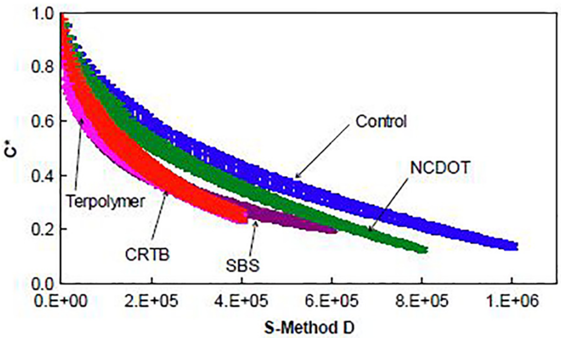

Fig. 11. Comparison of damage characteristic curves (Underwood et al., 2010).

$$C(S) = 1 - C_{11}S^{C_{12}} \tag{10}$$

$$N_f = \frac{(f_r)(2^{\alpha})S_f^{\alpha-\alpha C_{12}+1}}{(\alpha - \alpha C_{12} + 1)(C_{11}C_{12})^{\alpha}\left[(\beta+1)\left(\varepsilon_{0,pp}\right)\left(|E^*|_{LVE}\right)\right]^{2\alpha}K_1} \tag{11}$$

where

N_f = number of loading cycles at failure
α = damage evolution rate
f_R = reduced frequency
S_f = damage parameter at failure
C_{11} and C_{12} = regression coefficient of the power model used to fit the C-S curve
β = correction factor based on the mean of strain amplitude
$\varepsilon_{0,pp}$ = peak to peak strain amplitude
$|E^*|_{LVE}$ = linear viscoelastic dynamic modulus at the particular temperature and frequency
K_1 = calculated parameter depends on the time history of loading.

3.1.5.2. Smeared viscoelastic continuum damage modeling. The damage-only continuum approach does not consider the healing effect due to the rest period in the damage model formulation. Underwood and Zeiada (2014) observed that the rest period significantly reduces the damage development (Fig. 12) in bituminous mix due to the healing effect. Hence, they proposed a new improved S-VECD model by smearing healing into the damage formulation to take the healing effect into account. The laboratory fatigue life obtained using this model need not be transferred to a field value as required in the damage-only approach. In this approach, fatigue endurance limit refers to a strain level which results in 500 million load cycles i.e. highest number of load repetition expected in 40 years of life (Prowell et al., 2010).

3.1.5.3. Reduce cycle method. Christensen and Bonaquist (2009) developed a new continuum damage based approach using the concept of the reduced cycle and effective strain. The use of reduced cycle as given in Eq. (12) in place of the damage parameter (S) collapses the data at different temperature and strain values to a unique relationship (Fig. 13). This approach includes the effective strain parameter in the reduced cycle formulation to account for the endurance limit.

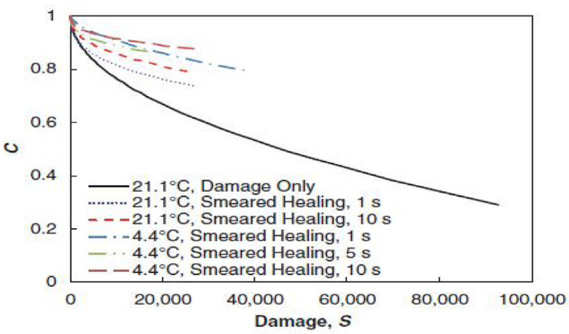

Fig. 12. Comparison of pure damage and smeared healing damage characteristic relationships (Underwood and Zeiada, 2014).

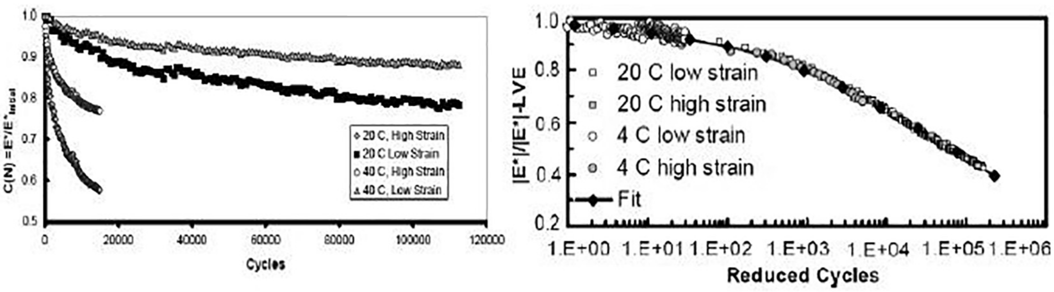

Fig. 13. Typical damage ratio curves (Christensen and Bonaquist, 2009).

$$N_R = N_{R-ini} + N\left(\frac{f_0}{f}\right)\left(\frac{|E^*|_{LVE}}{|E^*|_{LVE/0}}\right)^{2\alpha}\left(\frac{\varepsilon^E}{\varepsilon_0{}^E}\right)^{2\alpha}\left[\frac{1}{\alpha\left(\frac{T}{T_0}\right)}\right] \tag{12}$$

where

N_R = reduced cycle
$N_{R\text{-}ini}$ = initial value of reduced cycles, prior to the selected loading cycle
N = actual loading cycle
f_0 = reference frequency (10 Hz suggested)
f = actual test frequency
$|E^*|_{LVE}$ = initial (linear viscoelastic or LVE) dynamic modulus under given conditions
$|E^*|_{LVE/0}$ = reference initial (LVE) dynamic modulus (LVE modulus at 20 °C suggested)
α = continuum damage material constant with a typical value of about 2.0
ε^E = effective applied strain level, applied strain minus the endurance limit strain
ε_0^E = reference effective strain level (0.0002 suggested)
$\alpha(T/T_0)$ = shift factor at test temperature T relative to reference temperature T_0

To obtain the endurance limit, cyclic direct tension fatigue tests are performed at two strain levels and temperatures. The value of C and the corresponding reduced cycle is calculated. The C value is calculated by using Eq. (13).

$$C = \frac{|E^*|_n}{|E^*|_{LVE}} \tag{13}$$

where

$|E^*|_n$ = damaged modulus at cycle n.

A regression equation is developed between C and N_R, which generally takes the form as given by Eq. (14).

$$C = \frac{1}{1 + \left(\frac{N_R}{K_1}\right)^{K_2}} \tag{14}$$

where

K_1 = cycles to 50% damage (the fatigue half-life)
K_2 = fitting parameter

A numerical optimization is performed to determine the suitable value of the endurance limit for which the R^2 value of the regression equation is maximized.

Underwood and Kim (2009) tried to incorporate healing into the reduce cycle approach through pulse loading but observed that the testing time significantly increased.

3.1.6. Damage initiation approach

Endurance limit can also be defined as the strain value which will not develop any damage in the material i.e. the material will operate in its elastic zone. Any strain value just above the endurance limit will initiate damage in the material. Hence any strain value just below the damage initiation strain can be considered as the endurance limit. Based on this approach, the following methods can be used to find the endurance limit of different bound material.

3.1.6.1. Pseudo-strain method. The idea of pseudo strain was first coined by Schapery (1984), which is a virtual parameter to represent the actual physical strain in the elastic–viscoelastic correspondence principle. Using this principle, the constitutive equation of nonlinear viscoelastic medium is converted to nonlinear elastic to eliminate the viscoelastic effect. Bhattacharjee et al. (2009) used the pseudo strain parameter to determine the endurance limit of bituminous material. When a bituminous material is subjected to a strain value less than the endurance limit, it operates within the elastic–viscoelastic range and hence the plot between pseudo-strain (ε^R) and stress (Fig. 14) becomes a straight line (line of equality) (Nascimento, 2015). When damage occurs, the slope of the line of equality decreases and a loop between stress and pseudo-strain starts to develop (Fig. 15). This approach requires an increasing strain amplitude uniaxial tension test to be performed on the sample. The strain value at which the loop develops, is considered as the endurance limit. This method is superior to the extrapolation method or RDEC approach, as it is less time consuming, fundamental and takes into account the visco-elastic nature of HMA mixtures.

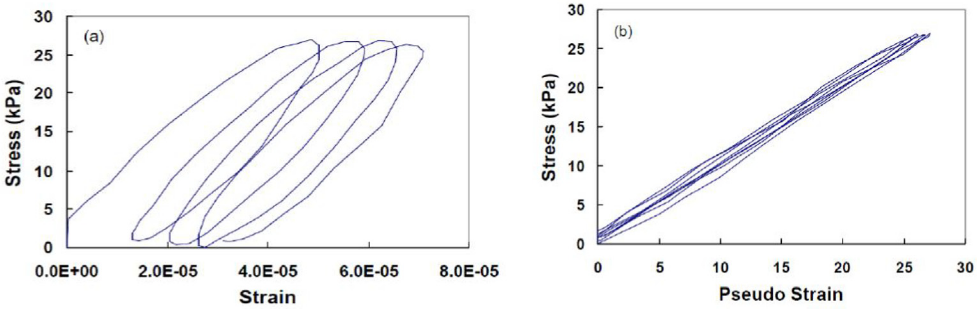

Fig. 14. Stress–strain and stress-pseudo strain behavior for controlled-stress cyclic loading within the materiaĺs LVE range (Nascimento, 2015).

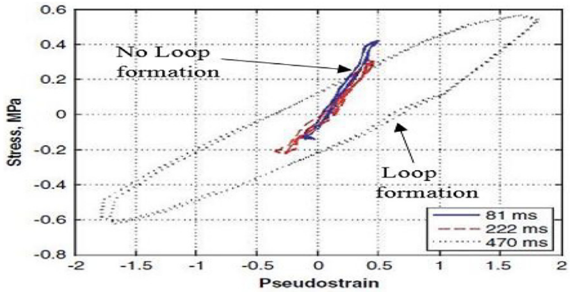

Fig. 15. Stress vs pseudo-strain at different strain levels (Bhattacharjee et al., 2009).

3.1.6.2. Soltani method. Soltani et al. (2006) developed a methodology using the uniaxial fatigue test to find the endurance limit, where three stages of continuous loading without any rest period are considered (Fig. 16). In Stages I and III, the strain level is kept below the endurance limit to avoid damage. During Stage II, a strain value exceeding the endurance limit is applied to induce damage in the material. The difference in modulus at the end of Stages I and III represents true damage. The strain value in Stage II is varied (Fig. 17) and the maximum strain value for which the modulus values at Stages I and III are same, is considered as the endurance limit.

3.1.7. Back-calculation method

The endurance limit in the field has mostly come from the evaluation of in-service pavements which are performing well without showing any sign of failure. During a study of existing pavements in the UK, Nunn et al. (1997) found that some

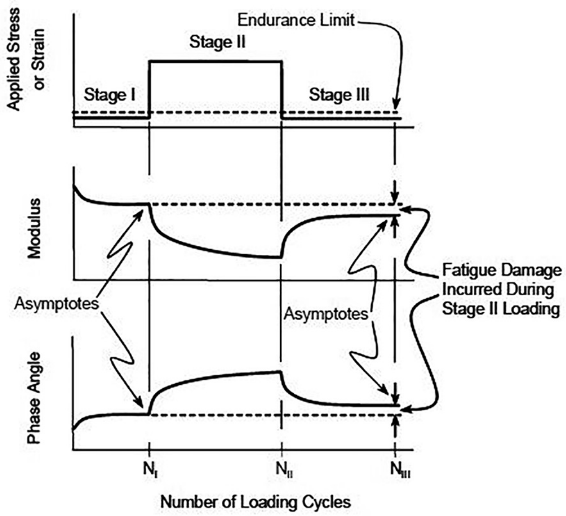

Fig. 16. Schematic of loading in Stages I, II, and III (Soltani et al., 2006).

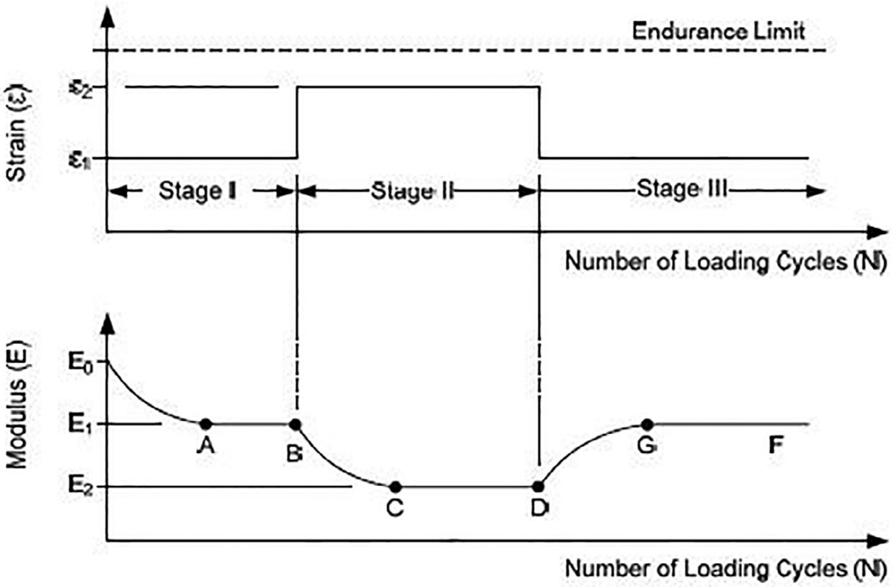

Fig. 17. Testing at specific strain levels to validate existence of the endurance limit (Soltani et al., 2006).

flexible pavements with thick bituminous layers (>180 mm) carried more than 100 million standard axles (MSA) and were still in a good condition. It strongly supported the existence of an endurance limit in pavements. Similarly, in-service pavements in Japan (Nishizawa et al., 1997), with tensile strain value at the bottom of the bituminous layer of less than 200 με did not experience any bottom-up fatigue cracking that validates the endurance limit concept. Kansas pavements also did not show any sign of bottom-up fatigue cracking at a tensile strain of 96–158 με (Wu et al., 2004).

3.2. Hydraulically bound materials

3.2.1. Threshold fatigue life method

For concrete and other hydraulically bound materials, endurance limit is defined as a strain/stress value which provides the material a threshold fatigue life. The following methods use this concept to find the endurance limit of different materials.

3.2.1.1. Portland cement association (PCA) method. Fatigue studies on Portland cement concrete (PCC) samples by various researchers as reported by Huang (1993) revealed that samples subjected to a stress ratio (SR) (flexural stress/static modulus of rupture) of 0.45 did not fail, even after being subjected to 10 million load cycles (Fig. 18). Later, PCA (1984) declared this value as the endurance limit value for concrete. In this method, 10 million load cycles is considered as the threshold fatigue life.

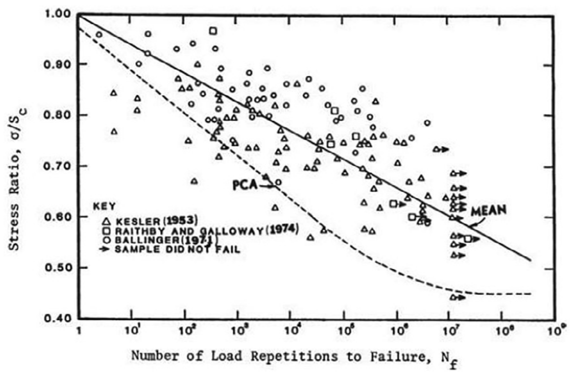

Fig. 18. S/N curve for concrete (Huang, 1993).

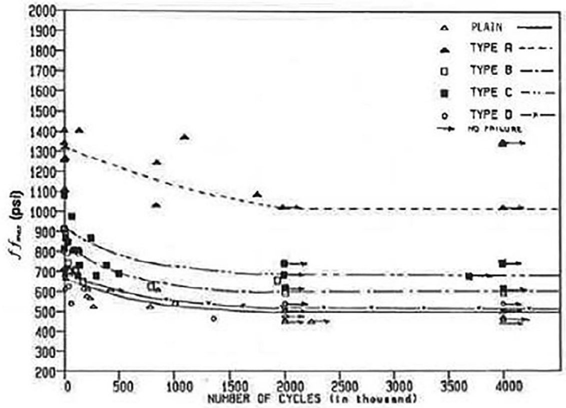

Fig. 19. Stress vs number of cycle (Ramakrishnan et al., 1989).

3.2.1.2. Two million cycle method. Ramakrishnan et al. (1989) defined the endurance limit for concrete as the stress level below which it can withstand the threshold fatigue life of 2 million loading cycles. They observed that the sample which did not fail within 2 million cycles, even sustained 4 million load cycles (Fig. 19). Therefore, fatigue tests were conducted at different stress levels to develop S-N curves and the stress value at 2 million loading cycle was reported as the endurance limit. Sobhan and Das (2007) adopted this approach for endurance limit determination of cement-fly ash stabilized recycled crushed concrete aggregates.

3.2.1.3. One million cycle method. Jitsangiam et al. (2016) suggested that the strain value resulting a fatigue life of 1 million cycles to be considered as the endurance limit as a laboratory fatigue cycle of 1 million is equivalent to 1.15×10^9 load repetitions in the field, using the laboratory-to-field shift factor of 1.2^{18} as suggested by Austroads (2014). This method is applicable for cement stabilized materials in strain-controlled beam fatigue test.

3.2.2. Damage initiation approach

3.2.2.1. Otte method. Otte (1977) observed that the stress–strain behavior of cement treated materials in flexure (Fig. 20) remain linear up to the critical loading condition, which is about 35% of the failure load and about 25% of the breaking strain. This conditions can be considered as the endurance limit, because within this limit the material behaves as a lineally-elastic material.

3.2.2.2. Envelope curve method. Aramoon (2014) studied the flexural fatigue behavior of fiber reinforced concrete and confirmed that fiber reinforced concrete has better post crack behavior than normal concrete. He observed that the sample can take more load cycles at a lower intensity load even after the fatigue failure. If a curve is drawn by connecting the maximum deflection points of the load–deflection curve throughout the fatigue life, or even after failure, it resembles the static load–deflection curve (Fig. 21). The curve is known as the envelope curve. This kind of observation was earlier reported by Bahn and Hsu (1998).

The total amount of plastic deformation up to the failure of a sample depends on the load intensity (i.e. the lower the stress level, the higher will be plastic deformation due to creep behavior). If the stress level is significantly lower, the envel-

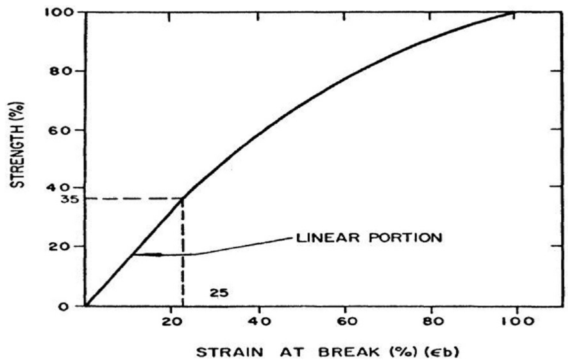

Fig. 20. General stress–strain curve of cement treated material in flexure (Otte, 1977).

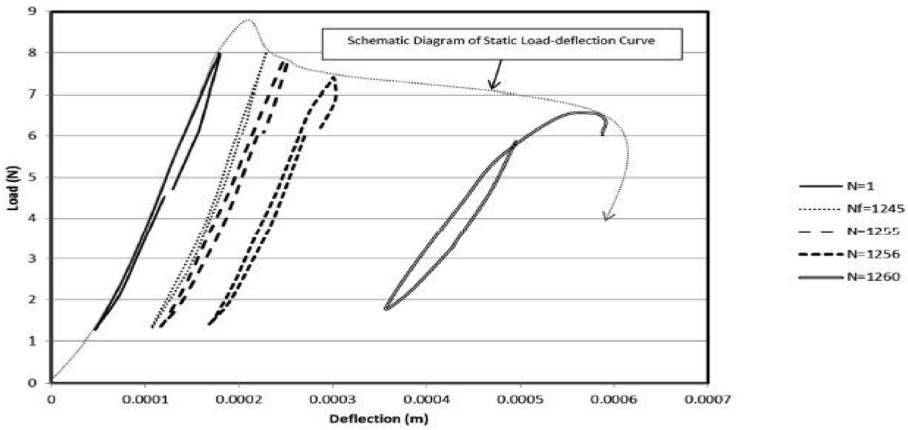

Fig. 21. A typical load–deflection curve showing envelop curve (Aramoon, 2014).

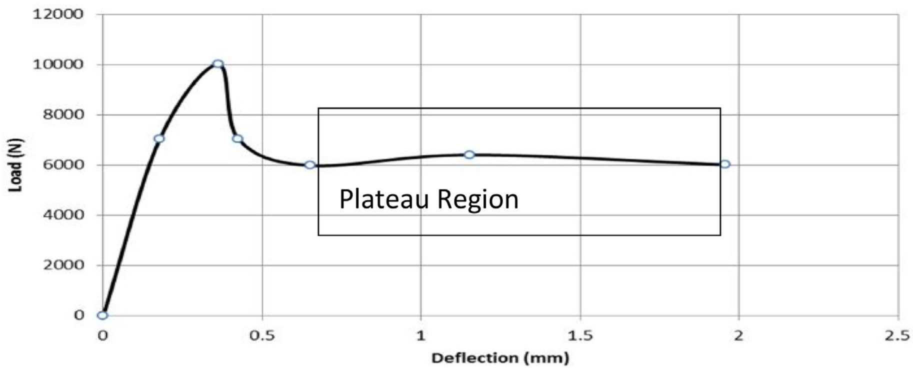

Fig. 22. Envelop curve showing plateau region (Aramoon, 2014).

ope curve attains a plateau where the load–deflection curve becomes flat (Fig. 22). This point may be considered as the endurance limit.

3.2.3. Back-calculation method

Parmeggiani (2012) conducted mechanistic back-analyses of some UK flexible composite pavements investigated by the Transportation Research Laboratory (TRL) in 1996 (Parry et al., 1997) and found that those pavements where the tensile strain ratio for the cemented layers was between 15% and 35% did not show any sign of fatigue failure, even after being subjected to more than 97 MSA repetitions.

4. Discussions

The following paragraphs critically discuss the various approaches adopted for determination of fatigue endurance limit of bound materials.

The convergence of fatigue data reported by Monismith and McLean (1972) shows that there is a definite change in the fatigue behavior of bituminous mixes at a low strain level of 70$\mu\varepsilon$, but the testing was limited to only 5 million cycles. Using the laboratory to field fatigue life conversion factor of 10 as suggested by Leahy et al. (1995), 5 million cycles in the laboratory would result in 50 million cycles in the field. A field fatigue life of 50 million cycles might be very high during the time period, when the Monismith and McLean (1972) tested the materials to be considered as long life, but recent data suggest that at least 500 million cycles in the field is desirable to be regarded as long life (Prowell and Brown, 2006). Therefore in the laboratory, fatigue testing for a longer duration (of at least 50 million cycle) is desirable to re-validate this concept.

Prowell and Brown (2006) tested a few materials up to 50 million cycles and used these data to validate different extrapolation techniques. The extrapolation techniques use the test data of relatively shorter duration for testing i.e.10 million cycles, to obtain the strain value which would last for 50 million cycles. They observed that the Weibull function is the most suitable model to extrapolate data at strain values close to and higher than the endurance limit, whereas a logarithmic model best suited fatigue data below the endurance limit. However, an extrapolation approach is not appropriate for this task, as it is silent on the initial stiffness reduction data in the model.

Extrapolation techniques seem to be promising, but it may not be suitable for routine determination of the endurance limit, as it is time consuming and not repeatable. Apart from consuming a lot of time in testing, extrapolation methods fail to explain the underlying concept of changes in material behavior at the endurance limit. Therefore, alternative approaches are needed, which are repeatable, less time consuming and could explain the intrinsic behavior of the material. This leads to the development of new approaches like the RDEC method, healing method, continuum damage methods, and damage initiation methods etc. These methods focus on the intrinsic material behavior and seem to be better than extrapolation methods.

The RDEC approach is simple to implement, but it is a time-consuming process as it requires a lot of tests to be carried out at different strain levels to develop the PV *vs* N_f curve. The pseudo-strain approach has its own demerit, as it is visually challenging to identify the loop formation (Zeiada, 2012), which can even occur due to experimental difficulties or data noise. To eliminate the subjective nature of this approach, Underwood and Kim (2009) suggested an alternate method using the change in slope of the stress pseudo-strain graph to identify the damage. In this approach, theoretically a slope value of less than 1 would indicate damage initiation, but practically considering specimen to specimen variability and data noise, a value of 0.95 is recommended as the threshold value.

Underwood and Kim (2009) compared three methods i.e. RDEC, pseudo-strain and reduced cycle, and found that the RDEC and pseudo-strain approaches predict similar results at two different temperatures, but the reduced cycle method predicts a higher value compared to other two methods. They observed that the endurance limit is not a fixed value, but rather a function of different parameters such as healing, aging, temperature, and rate of loading, etc. In another study, Zeiada et al. (2017) analyzed six different methods (i.e. healing method, S-VECD model, smeared healing with continuum damage model, RDEC approach, pseudo-strain analysis method and reduced cycles method) and reported that each method results in a different endurance limit value as the definition of the endurance limit is different for each method. It is very difficult to regard one of these methods as the most appropriate and therefore a field verification is needed for further judgment. For bituminous mixtures, apart from the methods followed to determine the endurance limit, mixture properties (i.e. binder content, binder type, air voids etc.), temperature and the rest period in a loading cycle have a significant impact on the endurance limit value (Witczak et al., 2013). Therefore, the endurance limit value cannot be generalized for the bituminous mixtures and rather each mixture should be tested separately.

Apart from the mixture properties and temperature, mode of testing has a significant impact (Witczak et al., 2013) on the endurance limit value. It is suggested to use beam fatigue test rather than the uniaxial test for endurance limit determination because

a) The uniaxial test is more time consuming, requires greater precision while performing the test to avoid premature failure and greater attention during analysis,
b) The current mechanistic pavement design and analysis systems use flexure strain data.

Unlike bituminous materials, not much research has gone into finding of the endurance limit of hydraulically bound materials. The existing methods described in Section 3.2, hint towards the existence of an endurance limit but does not provide strong evidence in support of it. The two million cycle method is derived from fatigue testing of PCC (up to four million loading cycles), which may not be considered sufficient enough to support the existence endurance limit. One million cycle method seems to be reasonable, but the shift factor should be decided carefully considering the high exponent value of 12. The envelope curve has been developed for fiber reinforced concrete as it can sustain load after failure due to the presence of fibers and therefore it may not be suitable for PCC or stabilized materials which exhibit brittle behavior.

Also, the approaches developed for bituminous mixes may not be directly applied to hydraulically bound materials as the former is a viscoelastic material and the latter a quasi-brittle material. Extrapolation techniques are time consuming but can be used for early research to establish the endurance limit. Healing approach is not suitable for hydraulically bound material as these material do not exhibit any healing property. Also, the effect of the rest period or loading frequency on the fatigue life of hydraulically bound materials is insignificant. The approach used in the pseudo-strain method can be used by simply replacing the pseudo-strain with the physical strain, as the pseudo-strain parameter is used only to eliminate the viscoelastic effect. The underlying theme of the pseudo-strain approach is to find out the strain value, which initiates damage in the material. Therefore methods which are based on the same approach used in the pseudo-strain method may be considered suitable for hydraulically bound materials too. Different techniques used for metal fatigue testing, like the thermographic method, acoustic or ultrasonic methods to detect damage may also be explored to determine the endurance limit of bound materials.

5. Conclusions

The design of perpetual pavement is based on the concept of endurance limit and therefore it should be chosen judiciously for a rational design approach. Different methods used to determine the endurance limit of bound material have been reviewed and it is found that each method is unique in its own way. The definitions of the endurance limit used in these methods are different, but the central idea of endurance limit is the same. Each method yields a different endurance limit value, even for the same material. It is difficult to consider a method as the most suitable method, but methods such as the healing approach and pseudo-strain approach can be favored over extrapolation methods during the routine determination of the endurance limit. Field verification is needed to decide which method provides accurate values of this endurance limit.

Hydraulically bound layers are common in designing long life composite pavements. Though these materials have shown signs of the presence of an endurance limit, the existing methods have failed to give sufficient evidence to confirm the claim. Further research is needed to study these materials in depth to develop a methodology for the determination of the endurance limit. Use of hydraulically bound material in perpetual pavement would further popularize the concept of perpetual pavements in developing countries like India as it would facilitate the use of marginal materials in pavement construction.

References

AASHTO T 321, 2003. Standard method of test for determining the fatigue life of compacted hot-mix asphalt (HMA) subjected to repeated flexural bending. American Association of State and Highway Transportation Officials, Washington, DC.
APA, 2002. Perpetual pavements: a synthesis. Asphalt pavement alliance (APA), Lanham, MD, p. 101.
Aramoon, E., 2014. Flexural Fatigue Behaviour of Fiber-Reinforced Concrete Based on Dissipated Energy Modeling Thesis (PhD). University of Maryland.
Austroads, 2014. Cemented Materials Characterisation: Final Report. Austroads, Australia. Research Report AP-R462-14.
Bahn, B.Y., Hsu, C.T.T., 1998. Stress-strain behavior of concrete under cyclic loading. Mater. J. 95 (2), 178–193.
Bateman, D., 2012. Laboratory Investigation of Fatigue Endurance Limits in Asphalt Concrete Thesis (PhD). The University of New Mexico.
Bhattacharjee, S., Swamy, A.K., Daniel, J.S., 2009. Application of elastic-viscoelastic correspondence principle to determine fatigue endurance limit of hot-mix asphalt. In: Transportation Research Record: Journal of the Transportation Research Board, No. 2126. Transportation Research Board of the National Academies, Washington, DC, pp. 12–18.
Carpenter, S.H., Ghuzlan, K.A., Shen, S., 2003. Fatigue endurance limit for highway and airport pavements. In: Transportation Research Record: Journal of the Transportation Research Board, No. 1832. Transportation Research Board of the National Academies, Washington, DC, pp. 131–138.
Christensen, D.W., Bonaquist, R., 2009. Analysis of HMA fatigue data using the concepts of reduced loading cycles and endurance limit. J. Assoc. Asphalt Paving Technol. 79, 377–416.
Ferne, B., 2006. Long-life pavements-a European study by ELLPAG. Int. J. Pavement Eng. 7 (2), 91–100.
Hou, E.T., Underwood, B.S., Kim, Y.R., 2010. Fatigue performance prediction of North Carolina mixtures using the simplified viscoelastic continuum damage model. J. Assoc. Asphalt Paving Technol. 79, 35–80.
Huang, Y.H., 1993. Pavement Analysis and Design. Prentice-Hall Englewood Cliffs, New Jersey.
Jitsangiam, P., Nusit, K., Chummuneerat, S., Chindaprasirt, P., Pichayapan, P., 2016. Fatigue assessment of cement-treated base for roads: an examination of beam-fatigue tests. J. Mater. Civ. Eng. 28 (10).
Leahy, R.B., Hicks, R.G., Monismith, C.L., Finn, F.N., 1995. Framework for performance-based approach to mix design and analysis. J. Assoc. Asphalt Paving Technol. 64, 431–473.
Maupin Jr, G.W., Freeman Jr, J.R., 1976. Simple Procedure for Fatigue Characterization of Bituminous Concrete. Federal Highway Administration, Washington, DC. Final Report No. FHWA-RD-76-102.
Mazars, J., 1986. A description of micro-and macroscale damage of concrete structures. Eng. Fract. Mech. 25 (5/6), 729–737.
Monismith, C.L., McLean, D.B., 1972. Structural design considerations. J. Assoc. Asphalt Paving Technol. 41, 258–304.
Monismith, C.L., 1992. Analytically based asphalt pavement design and rehabilitation: theory to practice. In: Transportation Research Record: Journal of the Transportation Research Board, No. 1354. Transportation Research Board of the National Academies, Washington, DC, pp. 5–26.
Nascimento, L.A.H., 2015. Implementation and Validation of the Viscoelastic Continuum Damage Theory for Asphalt Mixture and Pavement Analysis in Brazil Thesis (PhD). North Carolina State University.
Newcomb, D.E., Buncher, M., Huddleston, B.W., 2001. Concepts of perpetual pavements. In: Transportation Research Circular Number 503. Transportation Research Board, Washington, DC, pp. 4–11.
Nishizawa, T., Shimeno, S., Sekiguchi, M., 1997. Fatigue analysis of asphalt pavements with thick asphalt mixture layer. In: Proceedings of the 8th International Conference on Asphalt Pavements. University of Washington, Seattle, WA, pp. 969–976.
Nunn, M.E., Brown, A., Weston, D., Nicholls, J.C., 1997. Design of Long-Life Flexible Pavements for Heavy Traffic. Transportation Research Laboratory, Berkshire. TRL Report No. 250.
Otte, E., 1977. A Structural Design Procedure for Cement-Treated Layers in Pavements Thesis (D.Eng). University of Pretoria.
Parmeggiani, G., 2012. Design of long life flexible composite and deep strength asphalt pavements. 25th ARRB Conference – Shaping the future: Linking policy, Research and Outcomes. Perth, Australia.
Parry, A.R., Phillips, S., Potter, J.F., Nunn, M.E., 1997. UK design of flexible composite pavements. 8th International Conference on Asphalt Pavements. Seattle, Washington.
PCA, 1984. Thickness Design for Concrete Highway and Street Pavements. Portland Cement Association (PCA), Skokie, IL. Engineering Bulletin EB109P.
Prowell, B.D., Brown, E.R., 2006. Method of determining endurance limit using beam fatigue tests. International Conference on Perpetual Pavement. Columbus, Ohio.
Prowell, B.D., Brown, E., Anderson, R.M., Daniel, J.S., Swamy, A.K., Von Quintus, H., Shen, S., Carpenter, S.H., Bhattacharjee, S., Maghsoodloo, S., 2010. Validating the Fatigue Endurance Limit for Hot Mix Asphalt. National Cooperative Highway Research Program, Washington, DC. NCHRP Rep. 646, NCHRP 9-38 Project.
Ramakrishnan, V., Wu, G.Y., Hosalli, G., 1989. Flexural fatigue strength, endurance limit, and impact strengths of fiber reinforced concrete. In: Transportation Research Record: Journal of the Transportation Research Board, No. 1226. Transportation Research Board of the National Academies, Washington, DC, pp. 17–24.
Schapery, R.A., 1984. Correspondence principles and a generalized J-integral for large deformation and fracture analysis of viscoelastic media. Int. J. Fract. 25 (3), 195–223.
Shen, S.H., Carpenter, S.H., 2005. Application of the dissipated energy concept in fatigue endurance limit testing. In: Transportation Research Record: Journal of the Transportation Research Board, No. 1929. Transportation Research Board of the National Academies, Washington, DC, pp. 165–173.
Singh, G., Tiwari, D., Jain, P.K., Swami, A.K., 2016. A critical review of endurance limits of bituminous mixes for developing countries. Transp. Res.Procedia 17, 438–444.
Sobhan, K., Das, B.M., 2007. Durability of soil–cements against fatigue fracture. J. Mater. Civ. Eng. 19 (1), 26–32.
Soltani, A., Solaimanian, M., Anderson, D.A., 2006. An Investigation of the Endurance Limit of Hot-Mix Asphalt Concrete Using a New Uniaxial Fatigue Protocol. Federal Highway Administration, Washington, D.C.. Report Number FHWA-HIF-07-002.
Souliman, M., 2012. Integrated Predictive Model for Healing and Fatigue Endurance Limit for Asphalt Concrete Thesis (PhD). Arizona State University.
Tsai, B.W., Harvey, J.T., Monismith, C.L., 2002. High temperature fatigue and fatigue damage process of aggregate-asphalt mixes. J. Assoc. Asphalt Paving Technol. 71, 45–385.

Tsai, B.W., Harvey, J.T., Monismith, C.L., 2005. Using the three- stage Weibull equation and tree-based model to characterize the mix fatigue damage process. In: Transportation Research Record: Journal of the Transportation Research Board, No. 1929. Transportation Research Board of the National Academies, Washington, DC, pp. 227–237.

Underwood, B.S., Kim, Y.R., 2009. Analytical techniques for determining the endurance limit of hot mix asphalt concrete. Proceeding 2nd International Conference on Perpetual Pavement. Columbus, Ohio.

Underwood, B.S., Kim, Y.R., Guddati, M.N., 2010. Improved calculation method of damage parameter in viscoelastic continuum damage model. Int. J. Pavement Eng. 11 (6), 459–476.

Underwood, B.S., Zeiada, W.A., 2014. Characterization of microdamage healing in asphalt concrete with a smeared continuum damage approach. In: Transportation Research Record: Journal of the Transportation Research Board, No. 2447. Transportation Research Board of the National Academies, Washington, DC, pp. 126–135.

Witczak, M., Mamlouk, M., Souliman, M., Zeiada, W., 2013. Laboratory Validation of an Endurance Limit for Asphalt Pavements. National Cooperative Highway Research Program, Washington, DC. NCHRP Report 762, NCHRP 9-44A Project.

Wöhler, A., 1860. Versuche uber die Festigkeit der Eisenbahnwagenachsen; English summary (1867). Engineering 4, 160–161.

Wu, Z., Siddique, Z.Q., Gisi, A.J., 2004. Kansas Turnpike—An Example of Long Lasting Asphalt Pavement. In: Proceedings International Symposium on Design and Construction of Long Lasting Asphalt Pavements. National Center for Asphalt Technology, Auburn, AL, pp. 857–876.

Zeiada, W., 2012. Endurance Limit for HMA Based on Healing Phenomenon using Viscoelastic Continuum Damage Analysis Thesis (PhD). Arizona State University.

Zeiada, W.A., Underwood, B.S., Kaloush, K.E., 2017. Impact of asphalt concrete fatigue endurance limit definition on pavement performance prediction. Int. J. Pavement Eng. 18 (11), 945–956.