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Review

A review on fatigue and rutting performance of asphalt mixes

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Fatigue and rutting are very well known to be the two popular distresses that occur in road pavement. These are mainly due to the increase in the number of vehicles particularly those with high axle loads, due to the environmental conditions and also due to construction and design errors. As a consequence the service life of asphalt pavement is affected and will be decreased. Various researches reported that using additives such as different types of polymer and fiber in asphalt concrete (AC) could be a solution to postpone deterioration of AC pavement. This paper aims to highlight previous research works conducted on the effects of using different types of additives and aggregate gradation on fatigue and rutting resistance of AC mixtures. It was observed that fatigue and rutting resistance of AC mixture could be enhanced considerably by utilization of different types of additives such as fibers that can increase the amount of strain energy absorbed during fatigue and fracture process of the mix in the resulting composite. Also, fibers and polymers provide three-dimensional networking effect in asphalt concrete and stabilise the binder on surface of aggregate particles and prevent from any movement at higher temperature.

Key words: Asphalt pavement, fatigue, rutting, aggregate gradation, additives.

INTRODUCTION

Asphalt concrete is still a popular type of pavement because it provides considerable stability and durability as well as good resistance against water damage. The number of vehicles on roads is continuously increasing. According to the US Bureau of Transit Statistics, nearly 193 million registered vehicles used American roads in 1990 and the amount rose to over 254 million in 2007, while 135,932,930 of vehicles were classified as passenger cars and 6,806,630 of them were classified as trucks, single-unit 2-axle 6-tire or more (Bureau of Transportation Statistics, 2009).

Demand for road transportation is also growing among European countries especially between 1990 and 2005. It was predicted that freight traffic will increase by more than 66% from 1,706 billion tonne-kilometres in 2005 to 2,824 billion tonne-kilometres in 2030 (Mantzos and Capros, 2006). Also, in 2005 large amount of international goods transport, around 435 billion tonne-kilometres were observed by roads (European Commission, 2007).

Some undesirable effects can occur mainly due to high number of vehicles imposing repetitive higher axle loads on roads, environmental condition and construction errors. These usually cause permanent deformation (rutting), fatigue and low temperature cracking, service life of the road pavement is going to be decreased (Sengoz and Topal, 2005). Fatigue and rutting are the most common distresses in road pavement which result in the shortening of pavement life and increase maintenance cost as well as road user cost. So, it is vital to find out ways to delay the asphalt pavement deterioration and increase its service life. Many studies have been conducted to improve road pavement characteristics which can provide comfortable ride and ensure greater durability and longer service life against climate changes and traffic loading.

According to Arabani et al. (2010), there are two principal solutions to construct a more durable pavement; firstly, applying a thicker asphalt pavement which will

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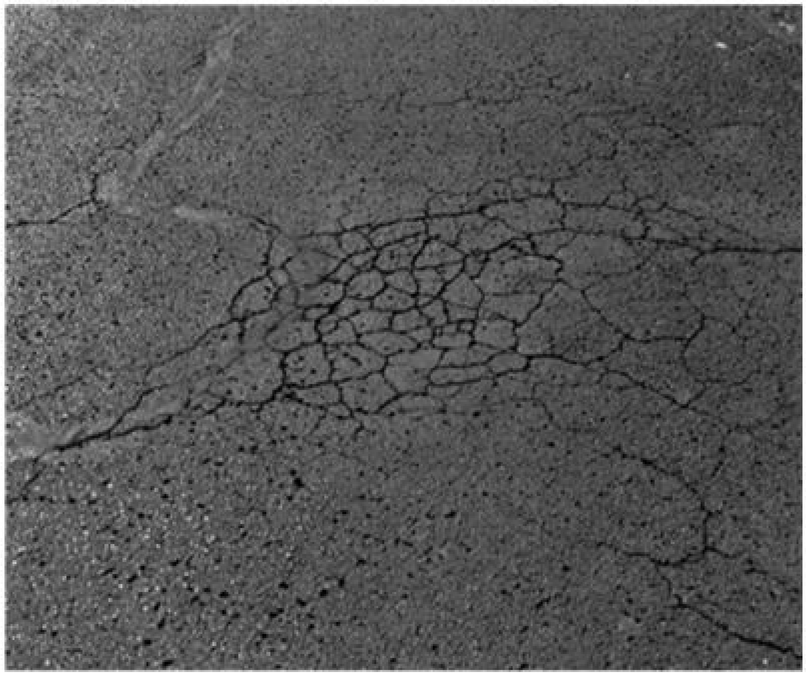

Figure 1. Fatigue crack (Alligator crack).

increase the construction cost and, secondly, making an asphalt mixture with modified characteristics. Modified binder (example, polymer modified binder) was also recommended to improve resistance of asphalt binder against rutting and thermal cracking (fracture of the pavement due to the lack of flexibility at low temperatures) of asphalt pavement (Lu and Isacsson, 2001; Navarro et al., 2004).

Using additives such as fibers and polymers in asphalt mixture can be a solution to improve high temperature rutting, medium temperature fatigue and low temperature cracking or in other words increasing the durability of pavement structure. Additives such as fibers absorb the amount of distresses imposed by repetitive heavy traffic loading during pavement life. A direct relationship exists between tensile strength of additives and engineering properties of asphalt concrete. In other words additives such as fibers can increase the amount of strain energy absorbed during fatigue and fracture process of the mix in the resulting composite (Mahrez et.al., 2005). Also, fibers and polymers provide three-dimensional networking effect in asphalt concrete and stabilise the binder on surface of aggregate particles and prevent from any movement at higher temperature (Xu et al., 2010; Jahromi and Khodaii, 2008; Ahmedzade et al., 2007).

This paper aims to review the laboratory experiences which were carried out on fatigue and rutting properties of asphalt mixtures containing different additives such as different fibers and polymers. These additives can be added to the mixture in two ways: wet process and dry process. In wet process specific amount of additives are being blended with virgin bitumen at a specific temperature and mixing time, then the modified bitumen would be added to the aggregate particles. In dry process the additives are being added to hot aggregates before blending with bitumen.

FATIGUE FAILURE OF ROAD PAVEMENT

One of the most significant distress modes in flexible pavements is fatigue. This distress(Figure 1) manifests itself in the form of cracking (example, alligator cracking), and it is associated with repetitive traffic loading and pavement thickness (Roberts et al., 1996; McGennis et al., 1994). Based on literature three phases are defined for propagation of fatigue cracks, namely, crack initiation, stable and unstable fatigue crackgrowth (Liang and Zhou, 1997). Fatigue cracks usually initiated in the form of microcracks and proceed to macrocracks, these cracks grow due to shear and tensile stresses in road pavement.

Fatigue life of pavement is affected by different properties of the mixture including type and amount of binder used in the mixture, temperature and air voids (NCHRP, 2004; SHRP, 1994). Also, it was observed that aggregate gradation is an effective factor for fatigue resistance of asphalt mixture even a lot more than the effects of asphalt content (Hafiang, 2001).

Fatigue behavior of the bituminous mixtures can be characterized by Beam Fatigue Test (Figure 2) or Indirect Tensile Fatigue Test (ITFT) (Figure 3) in controlled stress and strain modes. In addition, Dynamic Sheer Rheometer

Figure 2. Beam fatigue test (four-point bending).

Figure 3. Indirect tensile fatigue test (ITFT) apparatus.

(DSR) test is an effective way to analyse asphalt binder for fatigue and rutting performance (Muniandy et al., 2006; Chen and Xu, 2009).

Prediction of fatigue cracking in asphalt mixture

Based on the literature several equations are available in order to predict fatigue life of bituminous mixture. The most popular prediction equation of fatigue life is presented below:

$$N_f = c_1 \left(\frac{1}{\epsilon}\right)^{c_2} \text{ or } N_f = c_1 \left(\frac{1}{\sigma}\right)^{c_2} \quad (1)$$

N_f = number of cycle lead to failure

J = tensile strain at the bottom of asphalt layer

σ= stress

c_1 and c_2 are the regression constants; however, it was found that these parameters are dependent on variables such as properties of asphalt mixture, temperature and load.

In another equation, initial mix stiffness was also considered:

$$N_f = c_1 \left(\frac{1}{\epsilon}\right)^{c_2} \left(\frac{1}{s}\right)^{c_3} \text{ or } N_f = c_1 \left(\frac{1}{\sigma}\right)^{c_2} \left(\frac{1}{s}\right)^{c_3} \quad (2)$$

where

S is initial mix stiffness

c_1 , c_2 and c_3 are regression constants;

In addition, maximum strain can be calculated as the function of stress and stiffness modulus, for example the following equation was determined as the result of ITFT test:

$$\varepsilon_{max} = \frac{\sigma_{max}\,(1+3\upsilon)}{S_m} \quad (3)$$

where ε_{max} is maximum tensile strain at the centre of specimen,

σ_{max} is maximum stress,

S_m is stiffness modulus,

υ is Poisson's ratio.

A relationship between fatigue life and slope of accumulated strain was introduced. It was found that fatigue failure (without considering the temperature, aggregate gradation and loading magnitude) happened when the slope of accumulated strain moved from the decreasing trend to the increasing trend with the range of 42 to 46% (Abo-Qudaisand Shatnawi, 2007).

Furthermore, cumulative dissipated energy causing failure can be utilized in order to predict fatigue life of pavement using the equation below:

$$W = a(N_f)^b \quad (4)$$

where W is cumulative dissipated energy causing to failure using Equation (5),
N_f is the number of cycle lead to failure,
a and b are the coefficients determined empirically.

$$W = \sum_{i=1}^{n} W_i = \sum_{i=1}^{n} \pi \sigma_i \varepsilon_i \sin(\delta_i) \quad (5)$$

where W_i, σ_i and ε_i are dissipated energy, stress amplitude and strain amplitude at load cycle i, respectively. Besides, δ_i is phase shift between σ_i and ε_i. (Xiao et al., 2009).

As an important objective, crack growth speed is determined using Paris' law:

$$\frac{da}{dN} = AK^n \quad (6)$$

where a= crack length (mm)
N= number of load cycles
K= stress intensity factor
A and n are the parameters determined empirically.

Another modelling for fatigue life was devised by NCHRP on the foundation of continuum damage theory and an exponential damage rate:

$$N = \frac{2^{\alpha} f (C^{-\alpha} - 1)}{\alpha (-c_2)^{1+\alpha} . \epsilon_0^{2\alpha} |E^*|_{LVE}^{2\alpha}} \quad (7)$$

where N = fatigue cycles;
α = a material constant for viscoelastic material;
f = loading frequency, Hz;
C = damage ratio (damaged/undamaged modulus);
c_2= continuum damage fatigue constant;
ϵ_0= applied strain amplitude
E_{LVE}= linear viscoelastic (LVE) complex modulus

And parameter c_2 is computed by Equation (8):

$$C_2 = -30.1 |E^*|_{LVE}^{-0.629} . VFA^{-0.576} . R^{-1.54} \quad (8)$$

where R= Rheological index of binder (usually ranges between 1.2 to over 3.0)
VFA= void filled with asphalt (Christensen et al., 2006).

Fatigue behaviour of asphalt mixture, to a large extent is also influenced by the rheological properties of asphalt binder. It has been proposed that fatigue properties of asphalt binder can be evaluated by multiplying dynamic modulus with sine of phase angle (|E*| · sin δ) and these parameters are determined as the result of dynamic modulus test (Ye et al., 2009). Likewise, fatigue properties of asphalt binder can be assessed by Equation (9):

$$G'' = |G^*| \cdot \sin(\delta) \quad (9)$$

where (G″) = loss modulus parameter
|G*|and δ are complex shear modulus and phase angle, determined by dynamic shear rheometer test (Wu et al., 2008).

Effect of mix type on fatigue

An extensive study was carried out by Suo and Wong (2009) on fatigue characteristic of three types of asphalt concrete materials namely:

1. Gilsonite modified wearing course (GM-ACWC).
2. Stone mastic asphalt (SMA).
3. Conventional asphalt concrete wearing course.

The indirect tensile stiffness modulus (ITSM) was performed at four different temperature (10, 20, 30, 40°C). During the stiffness modulus tests, strain controlled mode was used. Moreover, the indirect tensile fatigue test (ITFT) was performed in both controlled stress and controlled strain modes. The results showed that average stiffness for GM-ACWC is considerably higher than other mixture types, but the results which were obtained from ITFT showed that Gilsonite modified ACWC has the longest fatigue life among the three at the strain level between 80 and 200 με,a range which is frequently used in pavement design. In addition, it was noted that fatigue lives of three mixtures are nearly the same at the strain of around 1000 με (Figure 4). Also, three dimensional finite element analysis using micro damage models, was selected to estimate fatigue crack growth under traffic loading. According to the results, the overall predicted fatigue lives of Gilsonite modified ACWC and unmodified ACWC were similar, and the two types of ACWC had a higher fatigue resistance than SMA (Suo and Wong, 2009).

A comparative study was done by Abo-Qudais and Shatnawi (2007) on three different HMAs with maximum nominal size of 12.5, 19 and 25 mm. It was observed that the larger gradation had the lower fatigue life, in other words the gradation containing 12.5 mm maximum nominal size had the highest fatigue life followed by the gradation containing 19 and 25 mm maximum nominal sizes.

Recently, Nejad et al. (2010) surveyed the effects of aggregate size, temperature and asphalt content on

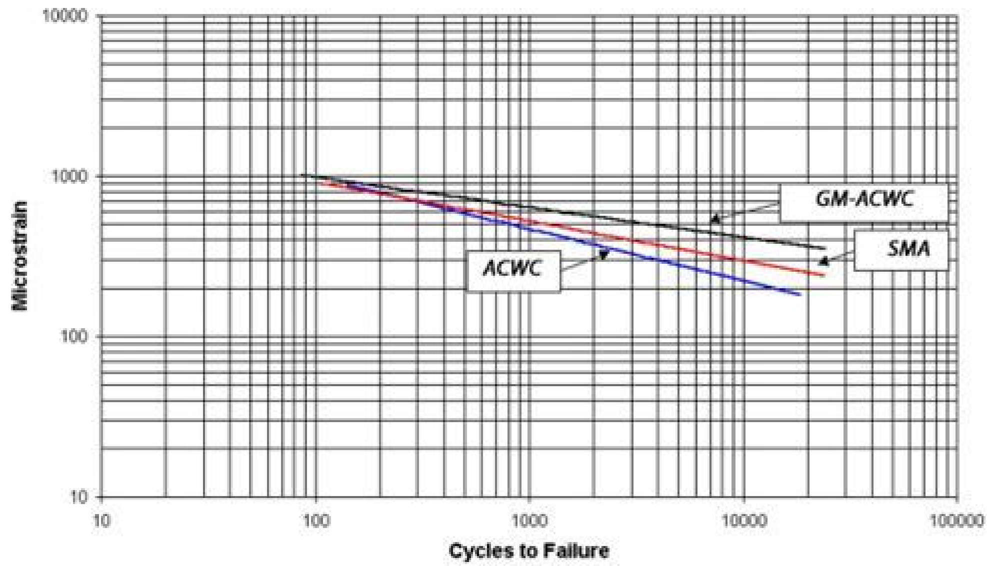

Figure 4. Results of ITFT on three different AC mixes.

fatigue characteristic of different asphalt mixtures. Indirect tensile stiffness modulus (ITSM) and indirect tensile fatigue test (ITFT) were employed in this study. It was found that the fatigue life was shortened with increasing temperature. Moreover, HMA mixtures had greater fatigue lives as compared to SMA mixtures and this arise from dense graded inherent structure which interlocked better to each other in comparison with SMA mixtures. It is concluded that increasing the asphalt content will make the mixture less stiff and therefore, less fatigue resistant (NCHRP, 2004).However, the effect of aggregate gradation on fatigue behaviour is more considerable than the effects of asphalt content (Hafiang, 2001).

Effect of additives on fatigue

Casey et al. (2008) used three distinct binders for stone mastic asphalt mixture namely, traditional pen and fibres binder (PF), a proprietary polymer modified bitumen used in practice (PMB) and the developed recycled HDPE modified binder (RP). For the PF mix a 40/60-pen bitumen was used in association with 0.4% fibres by mass of aggregate, also a blend based on 4% HDPE was optimised for RP binder. ITFT test was performed to assess each type of asphalt mixture. Each specimen was 100 mm in diameter and 70 mm in height and prepared using gyratory compactor. During indirect tensile fatigue test the specimens were subjected to a repeated constant load with 124 ± 4 ms loading time and pulse repetition time of 1.5±0.1 s at a temperature of 20°C. Finally, the strain level was plotted against the number of load cycles to failure. The results showed that PMB and PF have the highest and lowest fatigue resistance, respectively. Although the recycled polymer modified binder did not perform to the same high levels as the proprietary commercially available binder, it enhanced performance when compared with unmodified binders and binders containing cellulose fibres. These results suggest that the recycled polymer modified binder has great promise (Casey et al., 2008).

Xiao et al. (2009) published the earliest known study on fatigue behaviour of rubberized asphalt concrete mixtures containing warm asphalt additives (WMA). Two kinds of binder, PG 64 to 22 binder and PG 64 to 22 + 10% - 40 mesh ambient rubber, with addition of Asphamin and Sasobit as two warm asphalt additives were utilized, also two different sources of aggregate were used in this study, one of them was a type of granite which predominantly contains quartz and potassium feldspar (Type A) and the other type was schist (Type B). The beam fatigue test was conducted to assess the fatigue resistance of specimens. The tests were performed in a temperature-controlled chamber at 2 °C and a repeated sinusoidal loading at a frequency of 10 Hz was applied. Furthermore, controlled strain mode was employed. The results showed that Aggregate A has the greatest fatigue life as compared to Type B, although Aggregate B had the lower LA abrasion loss and absorption values. Moreover, regardless of aggregate sources the fatigue life of the mixtures made with crumb rubber and WMA additive is greater than the control mixtures (no rubber and WMA additive), except the mixtures containing Asphamin additive (Xiao et al., 2009).

Ahmedzade et al. (2007) published the result of a study in which they had assessed the effect of modified binder consisting of tall oil pitch (TOP) with and without SBS polymer with different percentage (8% TOP with 3,6,9% SBS) on fatigue and permanent deformation of asphalt mixture. Controlled stress mode at three loading values: 0.9, 1 and 1.1 and the frequency of 30 cycle/min with rest period of 1 s were considered for indirect tensile fatigue test at 25℃. They confirmed that the fatigue property of asphalt mixture with 8%TOP+6%SBS had the highest value. Besides, plastic deformation test was conducted at 45℃ with 100 kPa loading stress which is repeated 3700 times. It was observed that the control mixture has higher deformation with the ratio of 1.37/1 compared to modified mixtures (Ahmedzade et al., 2007).

Xu et al. (2010) investigated the effect of polyester, polyacrylonitrile, lignin and asbestos fibers with different percentages (0.00, 0.20, 0.35 and 0.50% by mass of mixture) on fatigue and rutting properties of asphalt concrete (AC) mixtures. Third-point bending fatigue test with stress controlled mode was performed at different stress ratios (0.1, 0.2, 0.3, 0.4 and 0.5) at 20℃. They investigated that addition of fibers into mixture also resulted in increment of fatigue life. As a result, fatigue life of AC with polymer fiber (polyacrylonitrile and polyesterfibers) was more than other mixtures. As mentioned in the study improvement of rutting and fatigue characteristic of AC is attributed to three-dimensional networking effect of fibers in AC and stabilisation of binder on surface of aggregate at higher temperature (Xu et al., 2010).

In another study which was carried out on fatigue properties of three types of fiber modified binder containing cellulose fiber, polyester fiber and mineral fiber. It was shown that the fatigue parameters $|E^*| \cdot \sin(\delta)$ (dynamic modulus $|E^*|$ and phase angle (δ)) were decreased, so the fatigue properties of fiber modified asphalt mixtures were improved compared to control mixture. Besides, the indirect tensile fatigue test (ITFT) was performed at different stress ratios, and the result illustrated that the polyester fiber had the best influence on fatigue resistance of mixture among the three (Ye et al., 2009).

In addition, Wu et al. (2008) investigated the effect of polyester fiber as a bitumen modifier they confirmed that the loss modulus ($|G^*| \cdot \sin(\delta)$) decreased as well as fatigue parameter ($|E^*| \cdot \sin(\delta)$), which is an effective parameter to characterize the resistance to fatigue cracking of asphalt binder.

In a related study, the effect of polypropylene fiber was evaluated on fatigue properties of asphalt mixtures (Huang and White, 1996). It was noted that the mixtures with polypropylene fiber had considerably more fatigue life in comparison with control mixture. Based on the results obtained by Tapkın (2008) the specimens containing 1% polypropylene fiber had 27% longer fatigue life than the reference specimens.

The addition of waste tire cord mesh with different percentages (0, 1, 2, 3 and 5% in terms of total bitumen weight) was investigated for fatigue and rutting characteristics of asphalt pavement. It was illustrated that the tire thread mesh improves fatigue and rutting properties of asphalt pavement, and sample containing 3% of tire cord mesh showed the best result. Besides, it is emphasised that the tire thread mesh postpone the crack initiation and propagation in asphalt pavement because of its characteristics such as high breaking and tensile strengths (Arabani et al., 2010).

In another research program the effect of cellulose oil palm fiber (COPF) with different percentages (0.2, 0.4, 0.6, 0.8 and 1% by weight of aggregates) was investigated for fatigue properties of SMA mixture. The wet process was considered for this study. The ITFT test was carried out at three different temperatures: 30, 40 and 50˚C, and two load levels 1000 and 1500 N were considered. It was observed that the mixtures with 0.6% COPF had the maximum fatigue life while the amounts for initial strains of SMA mixtures were at the minimum (Muniandy and Huat, 2006).

Mahrez et al. (2005) used various glass fiber contents in a study of SMA (0.1, 0.2, 0.3, 0.4 and 0.5% by weight of mix). Mixes were evaluated with dynamic creep and repeated load indirect tensile tests. The results showed that the use of glass fiber had a significant effect on fatigue life of mixes while fatigue life increased by about 28.2, 37.2 and 44.4% at fiber contents of 0.1, 0.2, and 0.3, respectively. Besides, permanent deformation properties could be improved by adding glass fiber. It is observed that the mixes containing 0.3% glass fiber showed the best deformation behaviour. This is because of well distributed fibers in different directions which improve shear resistance and prevent aggregate particles from any movement.This improvement in fatigue life is more considerable at higher stress level as compared to low stress level. Therefore the enhancement of glass fiber reinforced bituminous mix as fatigue barrier is more significant and useful when heavy trafficked road is concerned (Mahrez and Karim, 2010).

The effect of carbon fiber with the percentage of 0.1, 0.2, 0.3, 0.4 and 0.5% by weight of mix on fatigue life of mixtures was also studied (Jahromi and Khodaii, 2008). The samples were prepared at optimum asphalt content. Moreover, carbon fibers have been prepared with two different lengths: 12.5 and 20 mm corresponding to one and one and a halftimes the nominal size of the aggregates used in the study. ITFT test was conducted using constant repeated stress of 350 kPa with half sine pulse of 5 Hz frequency, 150 ms loading period and 50 ms rest period. It was illustrated that using carbon fiber showed great promise when the fatigue lives increased about 28.2, 37.2, and 44.4%, with the addition of 0.1, 0.2, and 0.3% carbon fiber, respectively. Distribution of fibers in different directions in bituminous matrix, which resisted the shear displacement and prevented aggregate particles from any movement was considered by author to justify the result. Also, it was observed that the specimens containing 20 mm fiber length had more fatigue life as compared to those mixtures containing 12.5 mm carbon fiber (Jahromi and Khodaii, 2008).

Figure 5. Permanent deformation in asphalt pavement.

Figure 6. Wheel tracking test machine.

Yan et al. (2010) determined fatigue properties of foam and emulsion cold recycled mixes. Mixtures were evaluated by indirect tensile stress testing and indirect tensile fatigue testing. The foam mixes were found to have a higher fatigue life at low stress level and the fatigue life for emulsion specimens are more than foam mixes at higher stress level (around 400 kpa). Also, they confirmed that foam cold mixes should be used as a base course, while emulsion cold mixes should be used as a binder mix (nearer to the surface). Besides, it was observed that fatigue failure of emulsion cold mixes had plastic fracture. In contrast, foam asphalt cold recycled mixes exhibited brittle failure.

RUTTING FAILURE OF ROAD PAVEMENT

Permanent deformation or rutting (Figure 5) accrues as a result of repeated loading due to heavy traffic loading which cause progressive accumulation of permanent deformation under repetitive tire pressures (Abdulshafi, 1988; Tayfur et al., 2007). Rutting performance has a close relationship with type of road construction, type of pavement and percentage of voids in asphalt mixtures. Also, rheological properties of asphalt such as penetration and viscosity could be effective factors (Muniandyand Huat, 2006; Lu and Redelius, 2007; Fontes et al., 2010).

There are different tests to assess the rutting resistance of asphalt mixture namely: wheel tracking test (Figure 6), static creep test, repeated-load creep test (Behbahani et al., 2009; Robertus et al., 1995; Stuart and Mogawer, 1997) Marshall Quotient (Shell Bitumen Handbook, 1991) and indirect tensile test. Also, marshal stability test to some extent has the correlation with rutting characteristics of asphalt mixtures (Li et al., 2002; Kim et al., 2000). In addition, it was noted by Özen et al. (2008) that repeated-load creep test (RLC) can be used as an indicator of potential rutting, but the result should be compared with other reliable tests.

Moreover, a test method base on applying a load to limited area was developed by Doh et al. (2007) to measure the resistance of the material at high temperatures. In this method the deformation is also taken into consideration. Deformation strength (SD) test was devised as a new test method to create a load-induced spot deformation, which is similar to the load imposed by a static wheel. Vertical static load at 50.8 mm/min was applied to the top of specimen through a loading head. Besides, to find a peak load point, the load was applied without confinement. As a result Equation (10) was developed:

$$SD = \frac{4P}{\pi\left[D-2\left(r-\sqrt{2ry-y^2}\right)\right]^2} \quad (10)$$

where:SD= deformation strength in pressure unit (MPa),
P= maximum load (N) at failure,
D= diameter (mm) of the loading head,
r= radius (mm) of curvature at the bottom of loading head,
y= vertical deformation (mm) in the specimen.

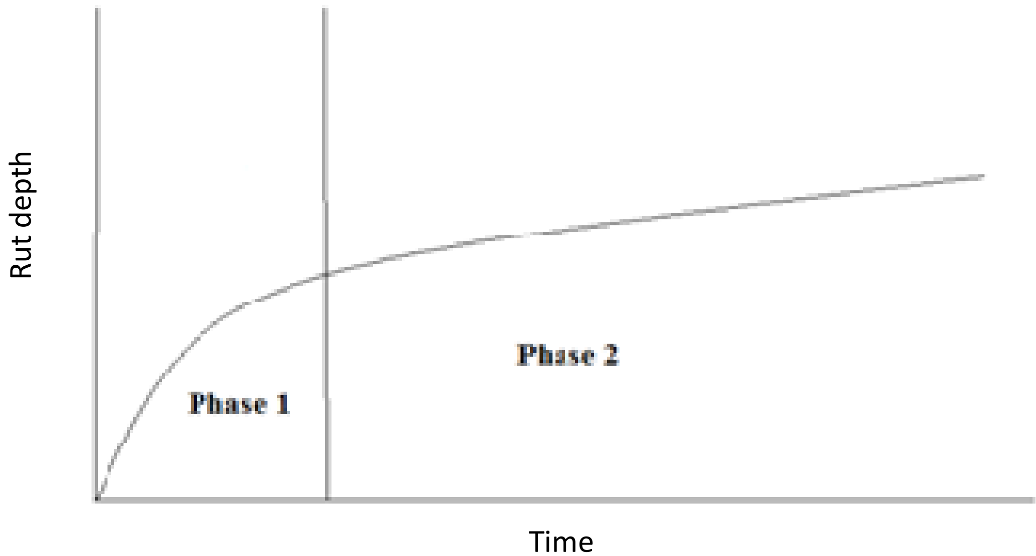

Figure 7. Rut depth vs. time.

For checking the accuracy of this method two different tests were also conducted. WTT test was performed at 60℃ with the pressure of 14.5 kPa and 30 cycles/min of speed. Mix design was conducted based on marshal method with 4% air void, 70 to 85% VFA, minimum marshal stability of 7.3(kN) and 20 to 40 flow values. For both SD and WTT tests a slab specimen was prepared, and two 100 mm-diameter cores were taken for SD test from the side of slab which was not used for WTT test. Besides, RLC was also conducted at 60℃ with 2.75 kN peak load. The result showed that there is inverse correlation between SD and rut parameters, Rut depth (RD) and dynamic stability (DS), with $R^2 = 0.9$ on the total average. Furthermore, there is a good correlation ($R^2 = 0.89$) between SD and RLC test. Finally, it could be noted that SD can be a good alternative test for rut tendency of asphalt concrete at high temperature (Doh et al., 2007).

Prediction of rutting in asphalt mixture

Different factors affect rut depth of AC, namely: vehicle speed, vehicle axel load, thickness of pavement and temperature as well as material properties of AC. Thus, finding an exact equation could be difficult. Also, previous researches illustrated that there is nonlinear relationship between rut depth and time at the beginning of pavement life (first phase), and this trend alters to a linear relationship during the time (second phase). In the first phase, asphalt pavement is compacted due to vehicle loads, and the rut depth increase considerably, while in the second phase rate of rutting decrease (Figure 7). Different studies were performed to find out rutting prediction equation for asphalt concrete pavement. Some of them are listed below:

Rut depth could be predicted by Equation (11):

$$RD = \alpha \times N^{\beta} \times T^{\theta} \quad (11)$$

where RD= Rut depth
N= Loading Repetition
T= Temperature, and
α, β and θ are the equation coefficient

Other prediction model for semi-rigid pavement was also determined in another study using Static Uniaxial Penetration Test (SUPT). The main advantage of this method is the consideration of shear parameters and speed in semi-rigid pavement:

$$RD = \alpha \times \left(\frac{V_{ref}}{V} \times Nv\right)^{m} \times T^{\theta} \quad (12)$$

$$m = \mu^{\frac{\tau}{\tau_0}} \quad (13)$$

where, Vref =is the reference speed
V= speed of interest
Nv= is the number of load repetitions at the speed of interest
T= Temperature
τ= Shear stress
τ_0= shear strength of asphalt mixture, and
α, θ and μ are the equation coefficient.
τ is shear stress and can be computed by the finite

element method, also:

$\tau_0 = k \cdot P_{max}$.

P_{max} is called penetration strength and can be obtained by the SUPT specimen,

k is shear strength coefficient (Su et.al., 2008).

In another study a rutting prediction model based on group method of data handling (GMDH) using accelerated pavement testing (APT) and NeuroShell 2 software was devised as below:

$$Y = -0.19 + 0.14 X_1 - 0.4 X_2 - 0.34 X_1X_2 + 0.83 X_2X_3 + 1.4 X_2^2 + 0.1 X_1^3X_2 + 0.32 X_1X_2X_3 + 4.9 X_2^3 - 3.5 X_2^4 - 14 X_2^5 + 1.8 X_2^6 + 9.8 X_2^7 - 0.5 X_2X_3^3 \quad (14)$$

where Y= 2* Actual rutting / 26.74 - 1

x_1= 2*(Wheel load -20) / 83.5 - 1

x_2= 2* Load repetitions /1131250 - 1

x_3= 2*(SN - 1.21) / 2.26 – 1

SN is called pavement Structure Number and obtained in accordance with AASHTO Design procedure.

To obtain this equation, APT test conducted at 23°C with different axle loads varied from 40 to 207 kN. In this study, a total of 264 records were considered as training data and 81 records for verification data as well, the R^2 value was in the same range for both training and verification records (Chang and Chao, 2009).

According to Christensen and Bonaquist (2006) there is a good correlation between rut rate and resistivity of mixture,

$$RR = 224P^{-1.08} * N_{eq}^{-0.65} * RD^{-18.06} \quad (15)$$

where, RR = Rutting rate, mm rutting/m thickness/ESAL$s^{\frac{1}{5}}$ (Equivalent single axle loads);

P = Resistivity, in s/nm;

$N_{eq} = N_{design}$ or number of blows with Marshall compaction hammer;

RD = Relative field density = (100% – in-place voids)/ (100% – design voids).

Besides, to evaluate rheological characteristics of asphalt binder at higher temperature, ratio G*/sinδ is mentioned as an effective parameter (Jun et al., 2008).

Effect of asphalt mix type on rutting

It was found that stone mastic asphalt(SMA) mixture has more resistance against rutting as compared to dense graded mixture, because it consists of coarse aggregate skeleton as well as higher asphalt content which provide stone-on-stone contact among the coarse aggregate particles (Scherocman, 1991; Scherocman, 1992; Davidson and Kennepohl,1992; Brown et al., 1997), although in another report the result was different (Asi, 2006). In addition, using mineral filler, such as lime stone powder, considerably improve the rutting performance of asphalt mixture (Superpave, 1996).

Effect of additives on rutting

Chiu and Lu (2007) conducted wheel track test on different asphalt mixture namely: SMA 13, SMA 19 (with and without ground tire rubber) and dense graded mixture. They indicated that rate of rutting (RR) for asphalt rubber (AR)-SMA had lower amount of rutin comparison with conventional SMA mixture with the same source of aggregate. Furthermore, it was observed that the mixture with bigger aggregate particle size had more resistance to permanent deformation. Thus, AR-SMA 19 and dense graded mixture had more and less resistance against permanent deformation, respectively.

Another study (Fontes et al., 2010) illustrated the effect of asphalt rubber binder on permanent deformation of asphalt rubber mixture containing two types of rubber obtained through the ambient and the cryogenic processes, with two different blends (continuous blend and terminal blend). The Repeated Simple Shear Test at Constant Height (RSST-CH) and the Accelerated Pavement Testing Simulator (wheel tracking) were conducted at 60°C to evaluate rutting resistance of asphalt rubber mixtures. In both tests it was observed that asphalt rubber mixture had lower permanent deformation compared to conventional mixture, and the majority of the permanent deformation occurred at the first loading cycles. It is interesting to know that asphalt rubber binder from continuous blend had the best result in both tests, and best permanent deformation behaviour was observed in the gap-graded asphalt rubber mixture with continuous blend. Linear relationship exists between the results obtained by RSST-CH test and wheel tracking test which confirms the accuracy of both tests for evaluating permanent deformation.

Effects of different rubber types namely: ambient and cryogenic and sizes (-40, -30 and -14 mesh) with a constant percentage of rubber (10%) and addition of 25% reclaimed asphalt pavement (RAP), was investigated on rutting and fatigue properties of asphalt mixture. The results showed that utilisation of crumb rubber and RAP improved rutting resistance of mixture considerably. Besides, it is investigated that ambient rubber with -30mesh size had the best result. Also, as mentioned in this survey, using RAP did not improve fatigue resistance of asphalt mixture, and on the contrary it had negative effect compared to virgin material. But, fatigue resistance increased with the addition of crumb rubber (especially ambient type) into the mixture (Xiao et al., 2009).

Cao (2007) published a study which illustrated the

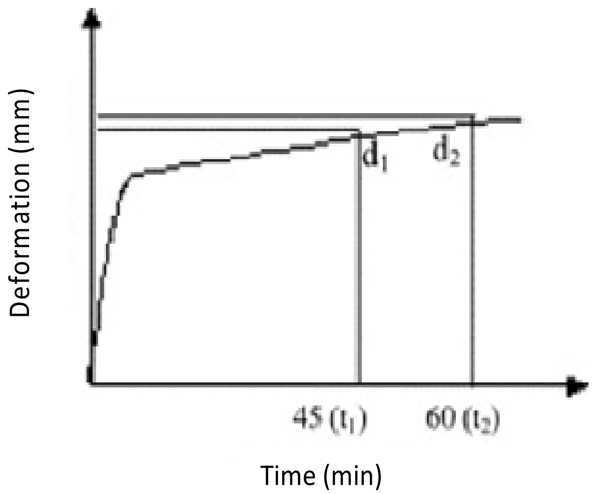

Figure 8. Diagram of deformation versus time.

effect of recycled tire rubber on rutting property of SBS-modified asphalt mixtures at high temperature. Different percentages of tire rubber (0, 1, 2 and 3%) were added to asphalt mixtures using dry process. WTT test with the load of 0.7 MPa and speed of 42 cycles per min was conducted to evaluate permanent deformation at 60℃. As a result the dynamic stability was calculated as follows:

$$DS = \frac{(t2 - t1) \times N}{d2 - d1} \quad (16)$$

where: DS is the dynamic stability,
d1 and d2 are deformation or rut depth in time 1 and 2;
t1 and t2 are the time after 45 and 60 min, respectively (Figure 8).
N is the number of cycles of wheel passes over the sample per minute.

The results indicated that DS increases with the increase of rubber percentage, so the sample containing 3% recycled tire rubber showed the highest resistance to permanent deformation (Cao, 2007). Note that higher DS means higher resistance to permanent deformation.

Another research program compared the rutting resistance of SMA mixtures containing two different kinds of polymer modified binders. One of them was proprietary polymer modified binder used in practice (PMB) and another one was developed recycled HDPE modified binder (RP). Wheel tracktest was employed to evaluate rutting parameters. Specimens were manufactured with dimensions 305×305×50 mm using a roller compactor and were typically allowed to rest at 20℃ for about 24 h. The rolling wheel with standard load of 520 N traversed the specimen at a constant speed of 21 load cycles per min for 45 min. Furthermore, in order to simulate a heavy loading and promote rutting all the tests were carried out at 60℃.

According to the result, the mixture with RP binder has good resistant against permanent deformation; however, the PMB binder mixture has better performance compared to RP binder mixtures. Nonetheless, utilizing recycled polymer binder could be encouraging to increase service life of pavement at high traffic condition (Casey et al., 2008).

Tayfur et al. (2007) investigated the effect of amorphous polialfaolefin (AP), cellulosefiber (SE), cellulose fiber mixed with bitumen (BE), poliolefin (PE) and stiren-butadien-stiren copolymer (SB) with the percentage of 6% of bitumen weight, 0.4% of mineral aggregate weight, 0.6% of total mixture weight, 0.6%of total aggregate weight and 5% of bitumen weight, respectively on rutting resistance of SMA mixture. Besides, for comparison different performance tests were conducted. Tests included: static creep test (uniaxial load of 425 kPa at 25 and 40℃ and 3600 s load duration), repeated creep test(with average load of1100 N and 1000 ms pulse period at the same temperatures) and LCPC rutting test (tire pressure of 0.6 MPa at 60℃). It was observed that all modified asphalt mixtures have more rutting resistance compared to conventional mixtures, and SBS mixtures have highest rutting resistance among all modified mixtures. Although the results obtained from static creep test was not coincident with other tests, so this test by itself cannot reflect the performance of modifiers. Moreover, it was observed that although the optimum asphalt content for modified asphalt mixtures are more than conventional mixture, the modified asphalt mixtures have more resistance against permanent deformation, and it may refer to more adhesion which exists between modified binder and aggregate particles (Tayfur et al., 2007).

In other investigation conducted by Hınıslıoğlu and Ağar (2004) it was observed that rutting resistance of asphalt mixture was improved by adding different percentage of waste high density polyethylene (HDPE) as bitumen modifier namely: 4, 6 and 8% by the weight of optimum bitumen content, it was noted that all specimens had approximately the same air void ratio which were between 3.07 to 3.35%. Besides, three different mixing temperatures (145, 155 and 165℃) and three different mixing times (5, 15 and 30 min) were considered in this study. Marshal Quotient (MQ) was considered for evaluation of permanent deformation. The specimen with higher MQ value has more resistant against permanent deformation. The result illustrates that the specimens fabricating with 4% waste HDPE at the 165℃ have more resistant to permanent deformation. Moreover,among all mixing time, 30 min of mixing period showed the best result when MQ increased 50% compared to control mixture.

Rheological properties of LDPE and GMA-g-LDPE modified bitumen containing different percentages of modifier (3, 4, 5 and 6% by weight of bitumen) were investigated by Jun et al. (2008). Due to low compatibility of LDPE and bitumen, Glycidyl methacrylate (GMA) was considered to improve polarity of LDPE. According to the result, the parameter G*/sinδ for GMA-g-LDPE modified bitumen was higher than that for base and LDPE modified bitumen. Thus, rutting performance of the GMA-g-LDPE PMB is better than that of the LDPE PMB, and this result illustrated that GMA-g-LDPE PMB have lower temperature sensitivity and better elastic performance. Also, bending beam rheometer (BBR) test showed that GMA-g-LDPE PMB did not reduce fatigue resistance at low temperature while adding LDPE had the negative effect on base bitumen (Jun et al., 2008).

Roofing shingle waste was used in a study by Sengoz and Topal (2005) in an attempt to evaluate the rutting behaviour of asphalt concrete mixes with shingle waste compared to control mixture (without shingle waste). 1% shingle waste by the total weight of mixture was selected as an optimum value. The LCPC pavement rutting tester was used with pneumatic wheel pressure of 600 kPa. The test was conducted at 60°C on the slab shaped specimen with dimensions of 500 × 180 × 100 mm, and pre-test loading condition (1000 cycles without preheating) was considered. As a result, it was illustrated that rut depth for specimen containing roofing waste shingle is considerably lower in comparison with control mixture.

Another research program illustrated rutting properties of SMA mixtures containing waste tire and carpet fibers in comparison with the mixtures using common cellulose and polyester fibers (Putman and Amirkhanian, 2004). Samples were fabricated based on Superpave mix design at optimum asphalt content. The cylindrical specimens were prepared with 150 mm diameter and 75 mm height, and were placed at 76°C for four hours before testing. Moreover, wheel load and hose pressure of 445 N and 689 kPa respectively were applied during the test. Rutting curve, rut depth versus cycles, was plotted for each mixture, and dynamic stability of each sample was calculated by determining the slope of the rutting curve after 1000 cycles. As can be seen from the result, the mixture containing polyester fiber showed the best rutting resistance with rut depth of 1.60 mm and dynamic stability of 10,299 cycles/mm; however, rutting resistance for all mixtures were nearly the same and no significant difference exists between these values when rut depth for mixtures containing carpet fiber, waste tire and cellulose fibers were 1.66, 1.67, 1.76 mm, respectively.

Xu et al. (2010) investigated the effect of polyester, polyacrylonitrile, lignin and asbestos fibers with different percentages (0.00, 0.20, 0.35 and 0.50% by mass of mixture) on fatigue and rutting properties of AC mixtures. Samples with dimensions of 30×30×5 cm were fabricated for WTT with the tire pressure of 0.7 MPa and speed of 42 cycle/min at 60°C.Results showed that AC with 0.35% polyacrylonitrile fiber had the lowest rutting depth after 2500 cycles which reduced by 32.56% in comparison with non-fiber mixture, while reduction values for polyester, lignin and asbestos fiber were 19.57, 8.43 and 11.40%, respectively.

Chen and Xu (2009) investigated the effect of two polyester fibers, one polyacrylonitrile fiber, one lignin fiber and one asbestos fiber on rutting properties of asphalt binder. In order to obtain rut parameter (G*/sinδ) and evaluate rheological properties of asphalt binder DSR test was conducted at 82°C and frequency of 10 rad/s under a constant torque. It was observed that asphalt binder with lignin fiber bhad the highest G*/sinδ (2.626 kPa)followed by Polyester fiber II, polyacrylonitrile fiber, Polyester fiber I and asbestos fiber with the amounts of 1.339, 0.961, 0.955 and 0.592 kPa, respectively. The highest amount for lignin fiber refers to highest absorption of light components of asphalt binder, and lowest amount for asbestos fiber was due to its smooth surface texture.

Also, another study (Liu et al., 2008) illustrated that addition of graphite powder into asphalt binder could enhance the asphalt characteristics against permanent deformation, when the rut parameter of graphite-modified asphalt binder (G*/sinδ) increased, example, from 1.555 kPa to 3.745 kPa at 40°C by adding 0 to 9.0% graphite powder into asphalt.

The effect of rock wool mineral fibers and cellulose fibers with different percentages (from 0.1 to 0.5% by weight of mixture) were also investigated for rutting properties of SMA mixture (Behbahani et al., 2009). Dynamic creep test was conducted to illustrate the rut tendency of SMA mixtures at 45°C, and average load of 1100 N was applied during 1000 ms pulse period. As the result the specimens containing 0.3% of cellulose-Ger and 0.4% cellulose-IRI and mineral fibers showed the lowest rut tendency in each category. Besides, the specimen with 0.3% cellulose-Ger had the lowest permanent deformation.

Another study (Jahromi and Khodaii, 2008) showed that small amount of carbon fiber considerably increase the resistance to permanent deformation. Also, it was noted that high amount of fiber leads to higher surface area that must be coated by bitumen, so bitumen could not coat fully the aggregate particles as well as fibers, thus the result decreased. Besides, it was illustrated that 4% of carbon fiber by weight of total mix lead to highest performance.

Özen et al. (2008) evaluated the rutting performance of asphalt mixture containing three types of elastomeric polymer modifiers namely OL (very cohesive product), EL (reactive elastomeric terpolymer) and SB (styrene–butadiene–styrene block copolymer) with different percentages of 5, 1.5 and 3%, respectively by weight of bitumen. LCPC wheel-tracking test and repeated creep test were conducted in this study. Repeated creep test was performed at 5, 25 and 40°C with average load of 1100 N. The result which was obtained from repeated creep test showed that the elastomer-modified asphalt mixture had better rutting performance than non-modified asphalt mixture, although different relations are observed at low (5°C) and high (40°C) temperatures. Besides, LCPC-wheel tracking test at 60°C with tire pressure of 0.6

MPa illustrated that OL and EL had the best result on rutting behaviour.

Akisetty et al. (2009) investigated the effect of two kinds of short-term aged warm asphalt additives (Asphamin and Sasobit) in rubberized binders produced by 10% of crumb rubber by weight of asphalt binder at the temperature of 177˚C and 30 min mixing time. In order to evaluate rutting properties of modified binder, DSR test was conducted and complex shear modulus (G*) and phase angle (δ) were obtained. Eventually, it was predicted that samples containing inorganic additive Aspha-min or aliphatic hydrocarbon Sasobit tend to have higher rutting resistance in comparison with control rubberized binder.

Lu and Redelius (2007) examined the effect of natural bitumen wax on rheological properties of bitumen and performance characteristics of asphalt mixture. They concluded that all the rheological properties of bitumen are mainly dependent on bitumen grade. For the 160/220 grade bitumen, effect of wax have not been observed, also for lower bitumen grade (70/100) wax may have adverse effect. In addition, wheel tracking test (WTT) was conducted with the tyre pressure of 0.6 MPa and speed of 2.5 Km/h at 60℃ to highlight the negative effect of wax melting on the rutting resistance. It was understood the rut depth for harder bitumen (example, 50/70) is lower as compared to softer bitumen with higher penetration grade. Besides, the mixtures prepared with waxy bitumen did not show deeper rut as compared to those with non-waxy bitumen.

CONCLUDING REMARKS

This paper aims to review previous studies conducted on fatigue and rutting properties of asphalt concrete (AC) and the effects of different kinds of additives on fatigue and rutting performance of AC to postpone the deterioration of asphalt mixture and minimize maintenance costs as well as construction costs. It was observed that mixture with larger aggregate gradation and higher asphalt content showed lower fatigue life, although larger aggregate gradation is a positive point for rutting performance of AC. In addition, it was observed that fatigue and rutting properties of AC can be improved by adding different types of additives such as different types of polymers and fibers as mentioned in this paper. Fibers and polymers can absorb a certain amount of distresses imposed by repetitive traffic loading during service life of pavement because of their inherent engineering properties. Also, they provide three-dimensional networking effect on the surface of aggregate particles and prevent aggregates from any movement. Among all of these additives, waste material has great promise to decrease cost of pavement as well as environmental pollution.

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