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Rheology and Simple Performance Test (SPT) Evaluation of High-Density Polypropylene (HDPP) Waste-Modified Bituminous Mix

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ABSTRACT

This study focuses on the evaluation of simple performance tests (SPTs), such as dynamic modulus, indirect tensile strength and rutting resistance tests, as it imparts on strength, service and durability requirements of high-density polypropylene polymer waste modified over conventional asphalt. The dynamic modulus test was carried out by Simple Performance Tester (SPT) or Asphalt Mixture Performance Tester (AMPT) using International Process Control (IPC) global test machine, otherwise called Universal Test Machine, with a pneumatic load of 25kN (UTM-25P) in accordance with AASHTO TP62-03 method, in order to determine modulus value, phase angle and recoverable strain. Indirect tensile strength evaluation was carried out using ASTM D4123-05a and ASTM D6931-12 recommendations. The recommendations followed for permanent deformation (rutting) were those stated in the NCHRP Report 508:2003 and AASTHO T324. The results showed that 2.0% HDPP asphalt performed optimally and gave enhanced results for dynamic modulus, ITS and rutting than conventional asphalt (control) for mitigating pavement distresses.

KEYWORDS: Asphalt, Strength, High-density polypropylene, Dynamic modulus, Rutting, Indirect tensile strength.

INTRODUCTION

Bituminous mixtures are complex and sensitive materials compared to others in civil engineering construction (Airey et al., 2008). Conventional asphalt pavements lack mechanical strength, service requirements and longevity to withstand heavy traffic loading, varying regimes of temperature loading and distresses induced by climatic and environmental conditions (Epps et al., 2000). It is important to assess the performance of pavement modifiers or reinforcing materials to withstand mechanical failure. Some of the prominent SPTs are: permanent deformation, fatigue cracking, thermal cracking, moisture susceptibility and friction properties (Brown et al., 2001).

Flexible pavements are susceptible to temperature and loading rate because of their visco-elastic and possibly plastic properties (Rais et al., 2013). Hot Mixed Asphalt (HMA) tends to be more viscous than elastic materials and the asphalt binder is in the flow state at high temperature and low frequency. There is a contrast

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between low temperature and high frequency when the asphalt mixture behaves as an elastic solid and glassy state material (Al-Khateeb et al., 2006).

Mechanical properties are fundamental properties of hot mix asphalt (HMA) in flexible pavement systems. Simple performance tests (SPTs) and performance durability criteria have been recommended by the National Cooperative Highway Research Program (NCHRP 9-19) to evaluate the properties in order to ascertain potential quality parameters that stand for testing strength, service conditions and longevity (Bonaquist et al., 2003).

SPTs are used to simulate actual field performance using laboratory mix design, as information provided by Hveem (stabilometer) and Marshall (stability and flow) are not adequate to understand the behavior of HMA owing to poor correlation between stability and flow (Whiteoak, 1990). NCHRP Report 465 showed that Simple Performance Tests (SPTs) are accurate and reliable and could measure the mixture response or characteristics that are correlated with the occurrence of pavement distresses by traffic and climatic conditions (Witczak et al., 2002). Other performance tests are: mix stiffness or dynamic modulus, resilient modulus, creep, wheel tracking and shear tests (ORN19, 2002). This research aimed at evaluating the possibility of using HDPP waste to improve mechanical properties of asphalt concrete.

Dynamic Modulus Test

Dynamic modulus test of HMA helps in determining its propensity to resist compressive deformation when subjected to cyclic compressive loading and unloading (Azari et al., 2007). The test is carried out by applying load sinusoidally to specimens over a range of different temperatures and frequencies (Shenoy and Romero, 2002). Applying a repeated load at varying frequencies to a test specimen over a relatively short period of time, the specimen's recoverable strain and permanent deformation can be determined. Viscous property, called complex modulus, E*, is the aggregation of storage or elastic modulus component and loss or viscous modulus. Figure 1 is a depiction of typical dynamic modulus. For visco-elastic tendencies of materials, according to Witczak et al. (2002), "complex modulus" (E*) is expressed by:

$$E^* = |E^*|\cos\varphi + i|E^*|\sin\varphi \tag{1}$$

where E* = complex modulus.
|E*| = dynamic modulus.
φ = phase angle – the angle by which ε_o lags behind σ_o.
i = imaginary number.

$$|E^*| = {}^{\delta_0}/_{\varepsilon_0} \tag{2}$$

δ_0 = peak stress amplitude (applied load / sample cross-sectional area).
ε_0 = peak amplitude of recoverable axial strain = ΔL/L.
ΔL = recoverable portion of change in sample length due to applied load.
L = original gauge length over which the sample deformation is measured.

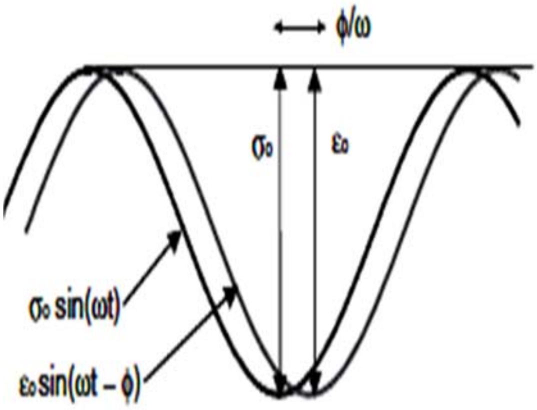

Figure (1): Dynamic (complex) modulus test

Data generated are used for plotting a master curve using the Sigmoidal curve fitting function to fit a master curve (Pellinen, 2002). This is given by:

$$\log(|E^*|) = \delta + \frac{\alpha}{(1 + e^{(\beta - \gamma \log f_r)})} \tag{3}$$

or

$$\log(|E^*|) = \delta + \frac{\alpha}{(1 + e^{(\beta+\gamma \log t_r)})} \quad (4)$$

where: |E*| = dynamic modulus (MPa).

f_r = reduced frequency (Hz).

t_r = reduced loading time (s).

δ = minimum modulus value.

α = span of modulus value.

β, γ = shape parameters.

The master curve shift factor is a time-temperature superposition and could be adapted from Arrhensius shift factor law given by:

$$\log[\alpha(T)] = log\frac{\Delta E_a}{2.303R}\left(\frac{1}{T} - \frac{1}{T_r}\right) = C\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad (5)$$

where

$\alpha(T)$ = shift factor at temperature T.

R = ideal gas constant = 8.314J/mol.K.

T_r = reference temperature in Kelvin, usually taken as 294.15K (Dougan et al., 2003).

ΔE_a= activation energy; the value of ΔE_a below T_r = 261kJ/mol (Abdelhaq, 2015).

C = constant with different values by different researchers [10920, 13060 and 7680K] (Medani and Huurman, 2003).

Finally, the reduced frequency, f_r, is given by:

$$f_r = f * \alpha_T \quad (6)$$

$$\log f_r = \log f + C\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad (7)$$

where f = reference frequency.

Tensile Strength

Tensile strength could be related to low temperature cracking of HMA and is a good cracking potential evaluator. The result of high tensile strain until failure shows that a particular HMA can tolerate higher strains before failing. This means higher propensity to resist cracking than HMA with low tensile strain to failure. Additionally, determining tensile strength before and after water conditioning could elucidate on moisture susceptibility of HMA. If the result of water-conditioned tensile strength is higher than the dry tensile strength, it can be reasonably assumed that the HMA is moisture resistant. There are two tests generally used to determine tensile strength of HMA: indirect tensile test and thermal cracking test.

Indirect tensile strength (ITS) test employs the same testing equipment as the diametral repeated load test and applies a constant rate of vertical load deformation till failure occurs. It is similar to splitting tension test of Portland Cement Concrete (PCC). AASHTO TP 9 is used for determining the creep compliance and strength of HMA using the indirect tensile test device as a standard example.

METHODOLOGY

Mechanical tests performed for SPT evaluation of asphalt are: dynamic modulus, indirect tensile strength and rutting resistance tests.

Dynamic Modulus Test

The test was carried out using a Simple Performance Tester (SPT) or Asphalt Mixture Performance Tester (AMPT) of International Process Control (IPC) global test machine, otherwise called Universal Test Machine, with a pneumatic load of 25kN (UTM-25P) in accordance with AASHTO TP62-03 and ASTM D3497 methods. It delivered a constant pressure of up to 2800 kPa in an environmental chamber conditioned to testing temperatures of 4.4, 21.1, 25, 45 and 60^{0}C to simulate ambient environmental temperatures. The test was accomplished by using gluing gauge plugs onto the specimen sides attached to a Linear Variable Differential Transducer (LVDT) to determine displacement.

A haversine dynamic loading (*Pd*) was adjusted such that axial strains lie between 75 and 125 microstrain (μm/m) without necessarily impacting in a cyclic manner. For each of the polymer-modified asphalt mixes, three (3) specimen replicates were prepared. Following the recommendations of AASHTO TP62, test loading frequencies considered were: 0.1, 0.5, 1, 5, 10 and 25 Hz, respectively. The recommended percentage air void (VIM) is 7±1.0% (AASHTO T312).

Indirect Tensile Strength (ITS) Test

The test comprises the measurement of compressive load, as well as vertical and radial displacements. It is used to determine the loading values for resilient modulus, fracture energy and fatigue resistance tests. It was carried out following the recommendations of ASTM D4123-2005a and ASTM D6931-2012 at a temperature of 25^0C.

Rutting of Asphalt Mix Test

Rutting resistance of asphalt mixes was determined using Asphalt Pavement Analyzer (APA) and load repetitions of 10,000 cycles to permanent deformation at 50^0C following the recommendations of NCHRP Report 508:2003 (Cooley et al., 2000) and AASHTO T324.

RESULTS AND DISCUSSION

Dynamic Modulus Test

At low temperature and high frequency or strain rate, asphalt mix exhibits more elastic behaviour, but as temperature increases and strain rate decreases, the viscous property becomes more prevalent. As the relationship between stress and strain becomes linear affected by temperature and frequency or time, the visco-elastic property of asphalt becomes linear too. Master curves were constructed to evaluate time-temperature superposition (TTS) and measure relationships between the physical quantities and dynamic modulus, phase angle and recoverable strain. Figures 2 to 9 show the TTS relationship for $|E^*|$ and ϕ.

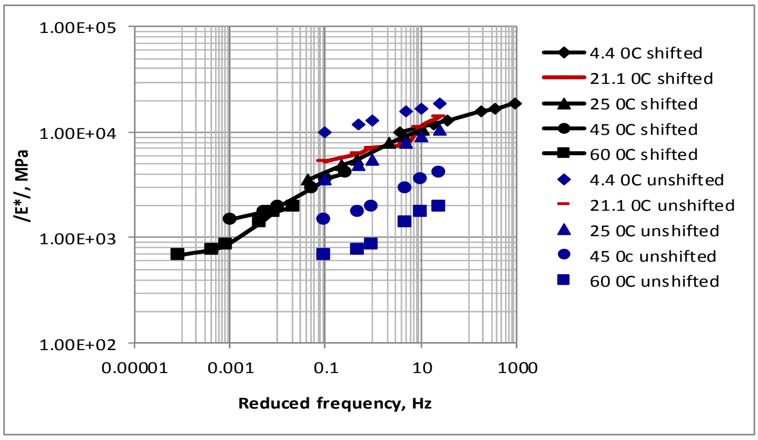

Figure (2): Dynamic modulus master curve ($|E^*|$) for 0% HDPP asphalt

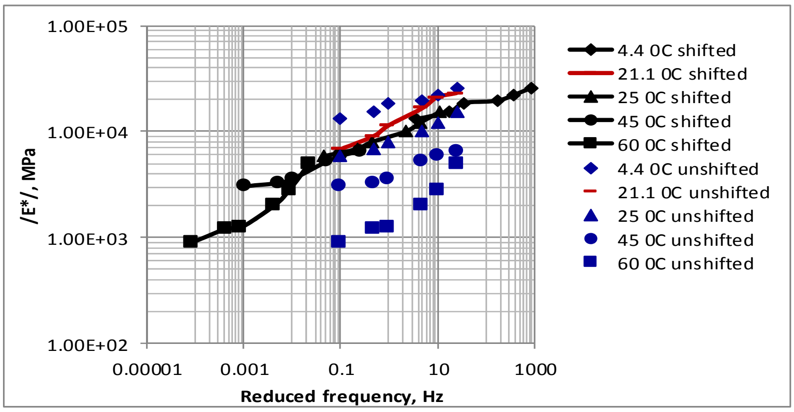

Figure (3): Dynamic modulus master curve ($|E^*|$) for 1% HDPP asphalt

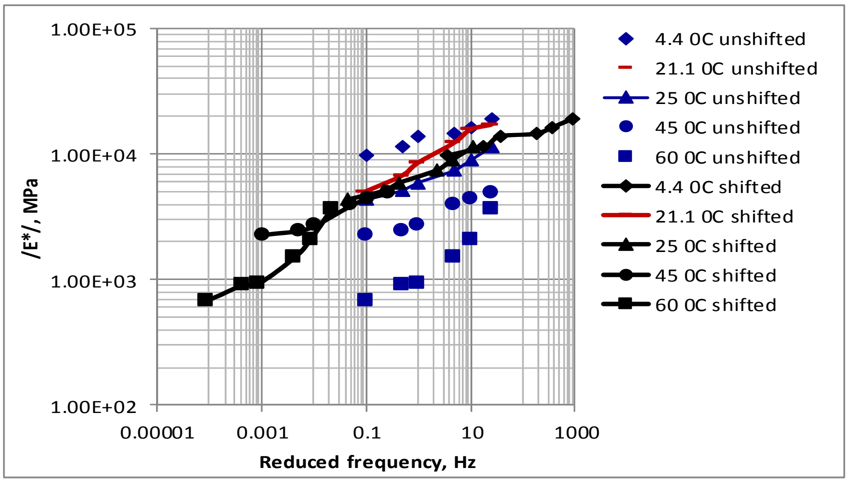

Figure (4): Dynamic modulus master curve ($|E^*|$) for 2% HDPP asphalt

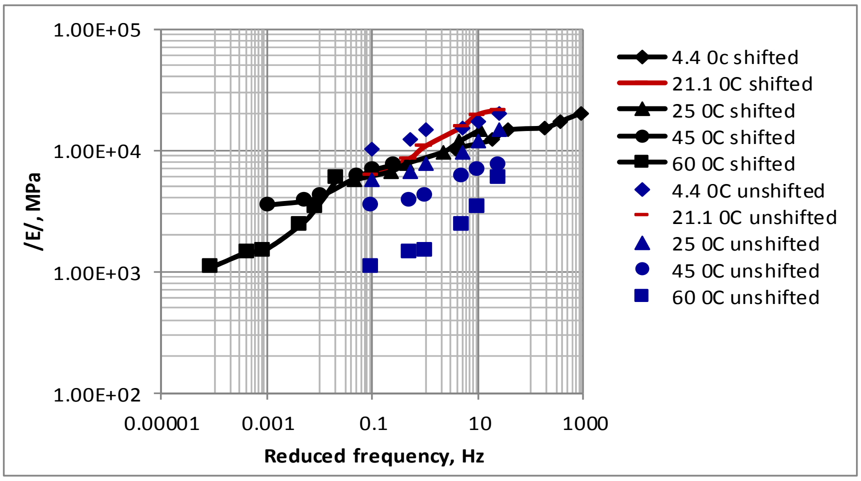

Figure (5): Dynamic modulus master curve ($|E^*|$) for 3% HDPP asphalt

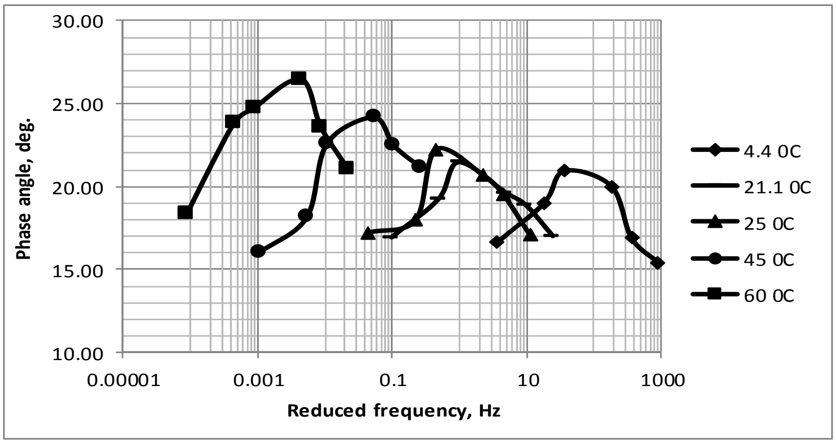

Figure (6): Master curve of phase angle for 0% HDPP PM asphalt

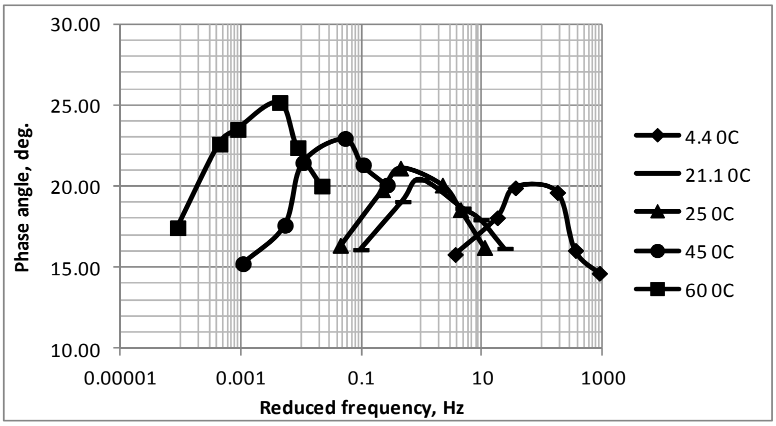

Figure (7): Master curve of phase angle for 1% HDPP PM asphalt

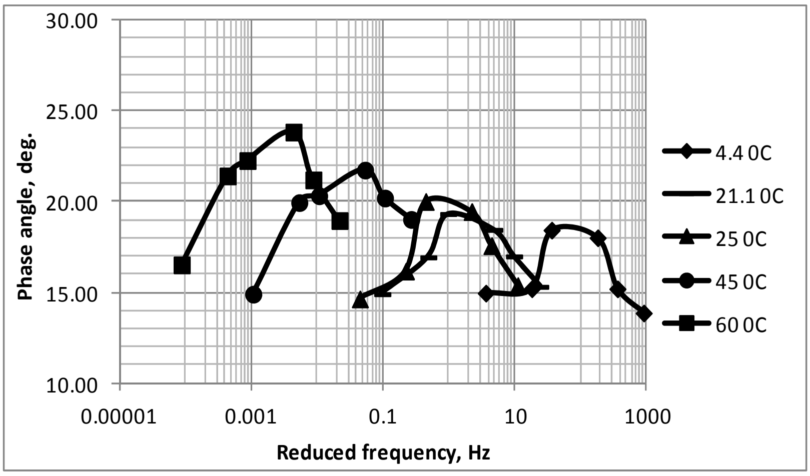

Figure (8): Master curve of phase angle for 2% HDPP PM asphalt

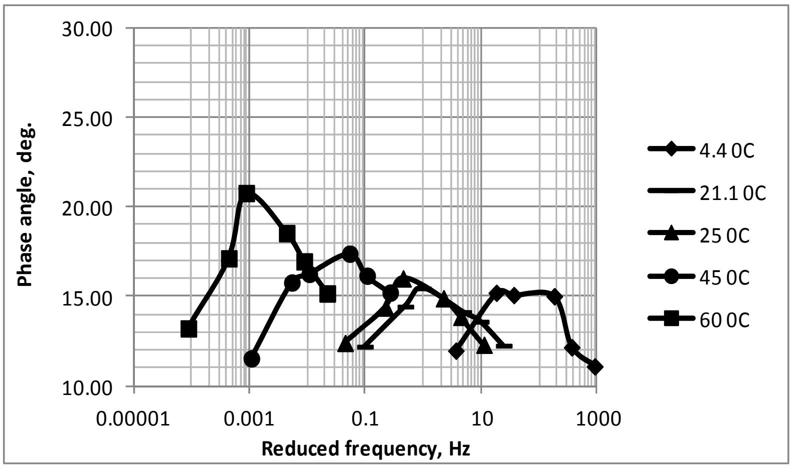

Figure (9): Master curve of phase angle for 3% HDPP PM asphalt

The results of dynamic modulus and phase angle tests are summarized as follows:

- The dynamic modulus, $|E^*|$ values increased from 0 to 2% HDPP content for the wet process because of increasing stiffness of the mix for all conditions of temperature and frequency used. This shows that dynamic modulus is sensitive to viscosity or penetration of bitumen which reduced with increasing polymer content. All the $|E^*|$ results meet the recommendable minimum of 1,500MPa by Hasim et al. (1994), but only at a temperature of 60^0C and lower frequencies from 1 to 0.1Hz, values of $|E^*|$ fell short of meeting the minimum and could perform poorly.
- At 3.0% HDPP polymer modification, the values of $|E^*|$ decreased, because more polymer phases in the bitumen matrix initiate more elastic response than viscous response at low temperatures ranging from 4.4 to 21.1^0C, but the increase in temperature from 25 to 60^0C increased visco-elastic and rheological performance of the mix. This visco-elastic relationship agrees with the findings of Lu et al. (2011).
- From 0 to 2% HDPP contents of wet process, the phase angle, ϕ, shows downward trends as a result of increasing elastic properties over viscous properties and reduction in deformation with respect to applied stress. The general trend of the results of ϕ increased with increasing temperature. But, the values of ϕ also increased to a peak before declining as frequencies reduced from 25 to 0.1Hz.
- The downward trend of ϕ for 3.0% HDPP polymer asphalt was a result of reduction in deformation initiated by plastic nature of more HDPP in the bitumen matrix which does not translate into strength of the mix.

Indirect Tensile Strength (ITS) Test

The following findings were obtained from ITS test:

- The average ITS results for 0 (control), 1, 2 and 3% HDPP polymer asphalt are: 1339.78, 1439.239, 1525.737 and 1447.45 kPa, respectively, as shown in Figure 10. The values of ITS for 0 to 3% HDPP polymer modified asphalt meet the minimum average ITS requirement of 1,100kPa recommended by ASTM D4123-05a and ASTM D6931-12; with 2.0% HDPP being the optimum. None of the values of ITS for polymer modified between the range of 0 to 3.0% is above the maximum of 1,700kPa, which is indicative of brittle failure and low flexibility of the mix.

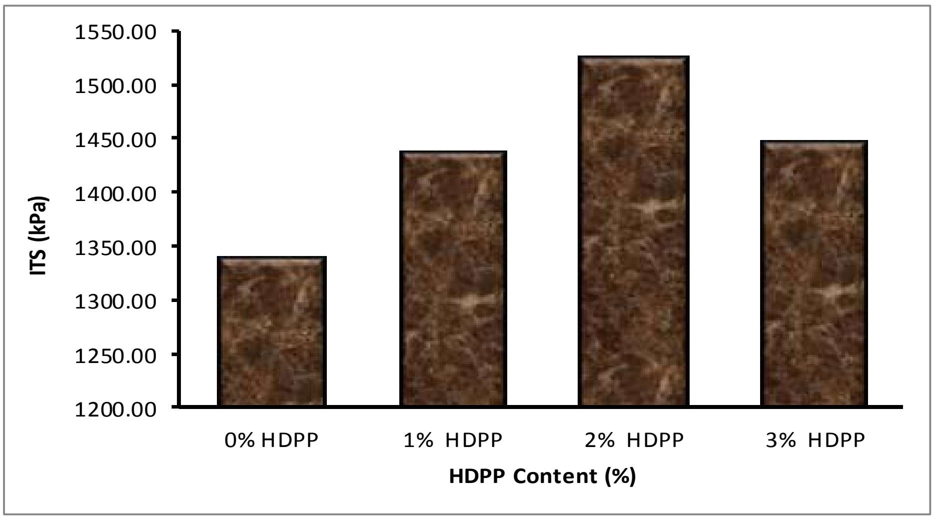

Figure (10): Average ITS results of asphalt concrete *vs.* HDPP content

Permanent Deformation (Rutting)

The following deductions were made from rutting evaluation conducted:

- The rut depths of 0 to 3% HDPP wet process were decreasing with increasing HDPP. The decreasing trend may be a result of increasing stiffness. From Figure 11, rut resistance increases with decreasing rut depth and values of 0 to 3% HDPP wet process are significantly below 8 mm recommended for 8,000 load cycles of NCHRP Report 508:2003 (Cooley et al., 2000) and 12.5 mm at 10,000 cycles of load repetition for AASHTO T324 recommendations.

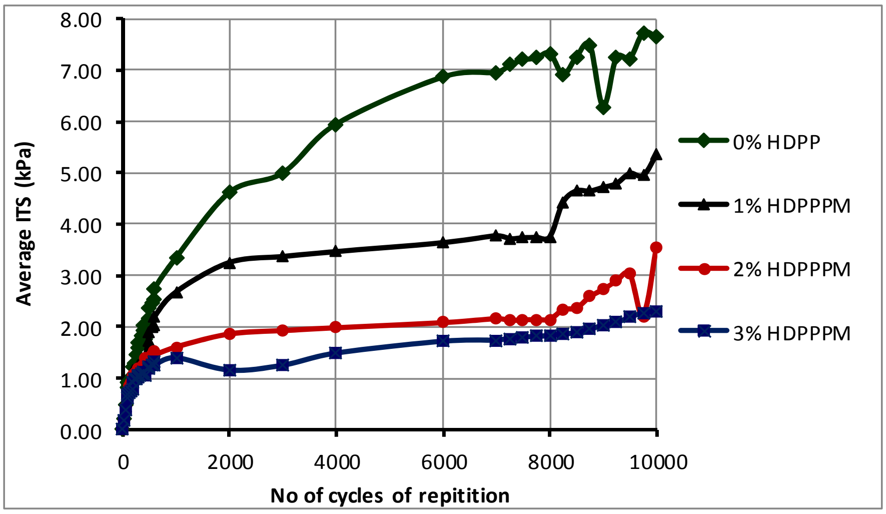

Figure (11): Asphalt rut depth against load cycle

CONCLUSIONS

From the results of dynamic modulus, ITS and rutting of HDPP asphalt mix evaluations, the following conclusions were drawn:

- The optimum /E*/ lies at 2.0% HDPP with about 50% increase in stiffness compared to the control (0% HDPP) for the entire temperature range of 4.4-60°C and frequencies of cycles of loading ranging between 25 and 0.1Hz.
- The optimum 2.0% HDPP reduces strain rate and lowers the value of φ to be able to withstand more cycles of loading.
- The ITS enhancement at the optimum of 2.0% HDPP could improve upon problems of low temperature cracking and moisture susceptibility of the asphalt mix.
- Rutting generally increases with increasing HDPP from 0 to 3.0%. The highest resistance to rutting at 3.0% HDPP could improve pavement performance at high temperatures, but 2.0% HDPP may be better at both low and high temperatures.
- For all SPTs conducted to evaluate /E*/, φ, ITS and rutting, 2.0% HDPP content performed optimally for heavy traffic situation simulated and could meet serviceability and durability requirements.

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