

Multi-Scale Numerical Viscoelastic Simulation of Fatigue Behavior of Asphalt Mixtures Modified with Polyphosphoric Acid

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Abstract. Fatigue cracking is one of the main distresses affects the service life of asphalt mixture. Recently, polyphosphoric acid (PPA) widely used as a modifier to improve mechanical and rheological characteristics of asphalt binders and mixtures especially at high and low service temperatures. While there are several studies devoted to investigate high and low service temperature of PPA modified asphalt binder and mixture, its fatigue behaviour needs to be studied in more detail. The main objective of this paper is to develop a multiscale heterogeneous numerical finite element (FE) model as well as experimental program to investigate the effect of PPA modification on fatigue behaviour of different bituminous composites from neat asphalt binder to asphalt mixture. The experimental program includes frequency sweep test at test temperature of 25°C by implementing dynamic shear rheometer (DSR) for neat and PPA modified asphalt binder and also indirect tensile fatigue (ITF) at frequency of 1 Hz (0.1 s loading time and 0.9 s rest time) under constant stress of 300 kPa at test temperature of 25°C by using a UTM-25kN. Three different contents of PPA is used for modifying neat asphalt binder including 0.5, 1 and 1.5 wt.% of neat binder to consider the variation of modifier extent on fatigue behaviour of neat asphalt binder and mixture. The mixture specimens were prepared with granite aggregate and asphalt binder of 85/100 penetration grade. The asphalt mixture is modeled as a biphasic medium composed of granular inclusions with linear elastic properties and bituminous matrix exhibiting linear viscoelastic behavior at small strain values. The generalized Maxwell rheological model was used to simulate viscoelastic behavior of the asphalt binder and PPA modified asphalt binder. In order to create the aggregate skeleton of the bituminous composites, a custom software (called "MOA", French acronym for Random Object Modeler) developed in University of Limoges, has been used to generate random inclusions of various sizes and shapes. The experimental results of asphalt binder and mixture indicated that modification with PPA has a significant effect on improving asphalt mixture's fatigue life especially in dosage of 1%. On the other hand, results of numerical simulation have shown a good agreement with experimental results.



1. Introduction

Asphalt mixture as a heterogeneous structure is subjected to numerous loading and unloading conditions during its service life which causes crack distresses in this structure. This material consists of bitumen, aggregate and air void in which aggregate has a wide range of particle size.

Although several studies have been considered asphalt mixture as a homogeneous material, but the fact is that this assumption makes an error in the behaviour simulation of asphalt mixture, because of its microstructure affection on the mechanical performance. The reason of this difference come out from the aggregate content, orientation and contacts etc. since it is necessary to consider the asphalt mixture as a heterogeneous material in order to investigate its performance and find more reliable response from the simulation [1, 2]. For this purpose, several simulation programs were proposed. One of these programs which developed by University of Limoges is MOA (French acronym for Random Object Modeler) which can generate a random distribution of aggregate particles based on aggregate curve for importing into commercial finite element software like ABAQUS.

It is well known that fatigue cracking is one of the major distresses of asphalt mixture which can be investigated by considering the heterogeneous combination. Using modifiers is a common approach for improving asphalt mixture's resistance against the fatigue crack. Polymers such as polyphosphoric acid (PPA), styrene Butadiene Styrene (SBS), PVE etc. are some instances of these modifiers that have been used recently in industry [3-7]. The PPA causes an improvement of high and low temperature performance of bitumen and asphalt mixture. While several studies have been also devoted during the recent decades [8, 9] to the use of this modifier for evaluating the asphalt mixtures distress, its fatigue behaviour needs to be studied in more detail. So, this research focuses on both experimental and numerical approach for evaluating the effect of PPA on fatigue behaviour of asphalt mixture. For this purpose, the fatigue behaviour of asphalt mixture as a viscoelastic heterogeneous material was investigated by performing experimental tests including the dynamic shear rheometer in frequency sweep mode on bitumen and asphalt mastic samples and the indirect tensile fatigue test on asphalt mixture and also applying a multi-scale numerical simulation. In this study, asphalt mixture is modelled as heterogeneous material containing irregular aggregate skeleton bonded with asphalt mastic.

2. Experimental program

In this paper, the fatigue behaviour of bitumen, asphalt mastic and asphalt mixture were studied. The bitumen with penetration grade of 85/100 (PG 58-22) and modified bitumen with PPA (by registry code 8017-16-1 Produced by Merck Company) were used. In this research, three different percentages of PPA including 0.5, 1 and 1.5% (based on weight of asphalt binder) was added to original bitumen. The PPA was blended with original asphalt binder implementing a low shear mixer at 150°C for 45 min. Table 1 depicts conventional properties of PPA used in this study based on producer's data sheet. Also, a well-graded Limestone filler was selected to construct asphalt mastic with volume relative of 18% ($V_{\text{filler}}/V_{\text{mastic}}=18\%$) according to aggregate curve and particle size distribution. Finally, asphalt mixtures were designed according to ASTM D1559 standard in which the optimum percentage of bitumen and air void was 4.7% and 5%, respectively. Figure 1 depicts aggregate curve of asphalt mixture. Considering the fact that PPA does not affect the optimum bitumen percentage, 4.7% of bitumen was assumed constant for modified asphalt mixtures.

Table 1. Conventional properties of polyphosphoric acid (PPA)

Property Title	Value
Boiling point	530°C (1013 hPa)
Density	2.06 gr/cm ³ at 20°C
Melting Point	-20°C
Vapor pressure	2 hPa at 20°C
Assay (acidimetric, calc. as P ₂ O ₅)	83 – 87%

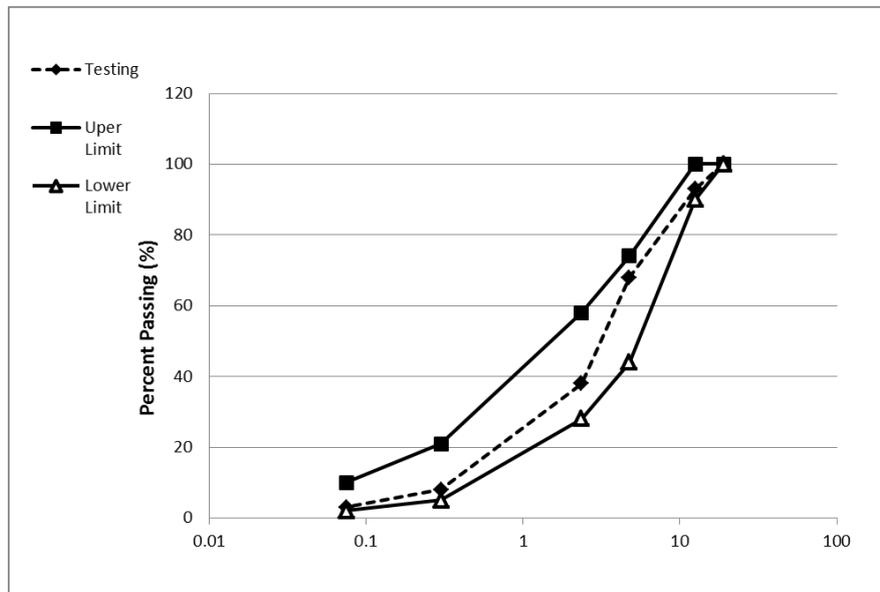


Figure 1. Aggregate Curve of Asphalt Mixture used in this study

The frequency sweep test at 25°C was conducted for bitumen and asphalt mastic to determine the rheological properties and also indirect tensile fatigue (ITF) at frequency of 1 Hz under constant stress of 300 kPa at 25°C was performed on asphalt mixture.

3. Methodology

The commercial software for numerical simulation is unable to develop randomly distributed particles. To overcome such a shortcoming, original software called MOA was written in C++ language based on the Delaunay triangulation method. This software can generate virtual models containing a matrix with a prearranged percentage of pores (volume filling rate) and given number of inclusions with different shapes including circle and polygon in 2D. It should be noted that MOA is capable of automatically generating samples derived from a matrix with a given percentage of air voids and containing a known number of inclusions featuring different shapes, extending from spherical to polyhedral and randomly distributed in the volume defined by the matrix in the form of a rectangular prism or cylinder.

In this research, the MOA is used to randomly generate aggregate inclusions and build up heterogeneous numerical model using the four following steps: 1) generating the main cadre of numerical model as a circle in two-dimensional domain to simulate ITF test, 2) generating inclusions arrangement with respect to gradation curve considering coarse and fine aggregate particles, 3) applying the Boolean operation to create the matrix and 4) assembling generated matrix and aggregate inclusions into one model by using function “Tied” in the ABAQUS software to tie the surfaces of aggregates and asphalt binder together. Figure 2 shows an example of two-dimensional models developed using MOA and ABAQUS.

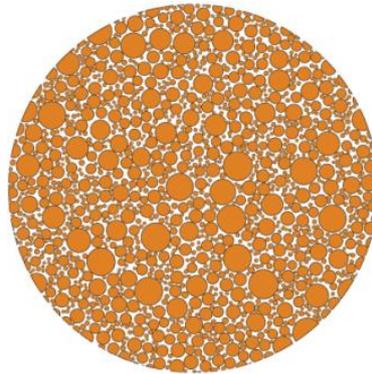


Figure 2. A 2D cylindrical model for simulating indirect tensile fatigue test

4. Results and Discussion

Figure 3 shows results of IDT fatigue test in which strain was sketched versus number of cycles to failure. As it can be seen in this figure, adding PPA obviously increases number of cycles to failure for all asphalt mixtures which shows positive effect of this modifier on fatigue behaviour of asphalt mixtures at moderate temperatures. According to these results, using 1% of PPA has more significant effect on improving the fatigue performance of asphalt mixture even in comparison with dosages of 1.5% of PPA. Therefore, 1% was obtained as the optimum dosage of PPA. Also using the dosage of 2% of PPA caused an extreme stiffness in bitumen during sample preparation process which makes some problems such as increasing in mixing temperature and compaction temperature of asphalt mixture. since, the usage amount of 2% was removed from selections.

In order to verify numerical model which is proposed for multi-scale approach, the loading and boundary conditions of experimental test was applied to numerical model which was developed for asphalt mixture. Constructing such a numerical model was done by using three following procedures:

- 1) Constructing asphalt mastic: considering asphalt binder as matrix and combining filler particles with binder as inclusions based on volumetric ratio of filler particles,
- 2) Constructing asphalt mortar: considering asphalt mastic as matrix and combining fine particles (< 1 mm) with asphalt mastic as inclusions based on volumetric ratio of fine aggregate particles,
- 3) Constructing asphalt mixture: considering asphalt mortar as matrix and combining coarse particles (> 1 mm) with asphalt mortar as inclusions based on volumetric ratio of coarse aggregate particles.

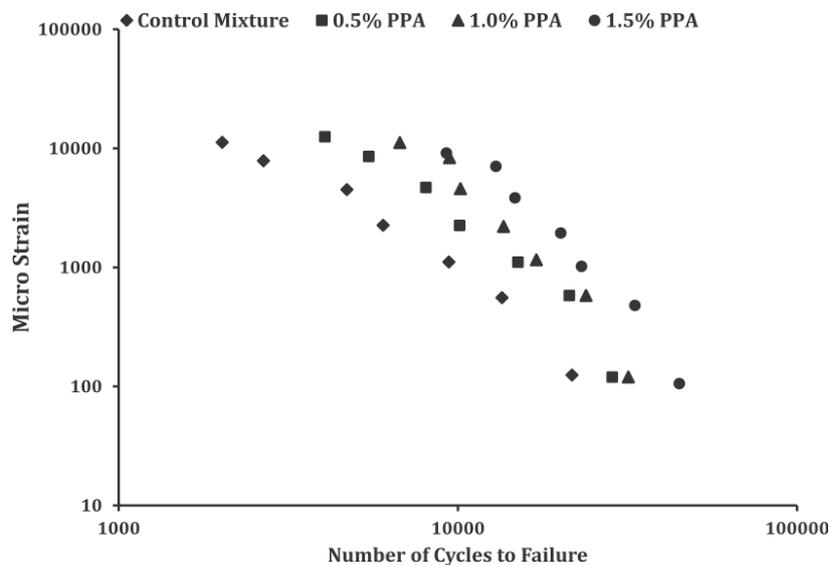


Figure 3. Strain versus number of cycles to failure for original and modified asphalt binders

To start numerical modelling with original and PPA modified asphalt binders, a generalized Maxwell model was used which is depicted in Figure 4 by implementing the Eq. (1) as follows:

$$G(t) = G_{\infty} + \sum_{i=1}^m G_i \exp(-t/\tau_i) \quad (1)$$

In which, G_{∞} and G_i are the equilibrium modulus and the shear relaxation strength, respectively and τ_i is relaxation time. Also, m is number of the generalized Maxwell model element. In this study, the number of components of the generalized Maxwell model is selected equals to 22 to provide accurate material characterization.

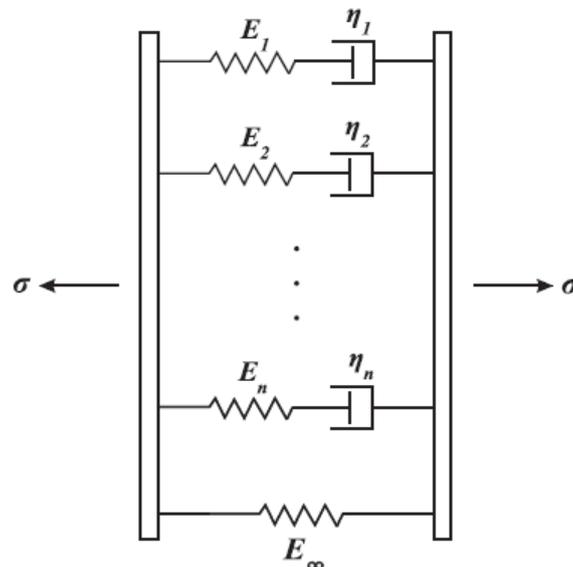


Figure 4. The generalized Maxwell model

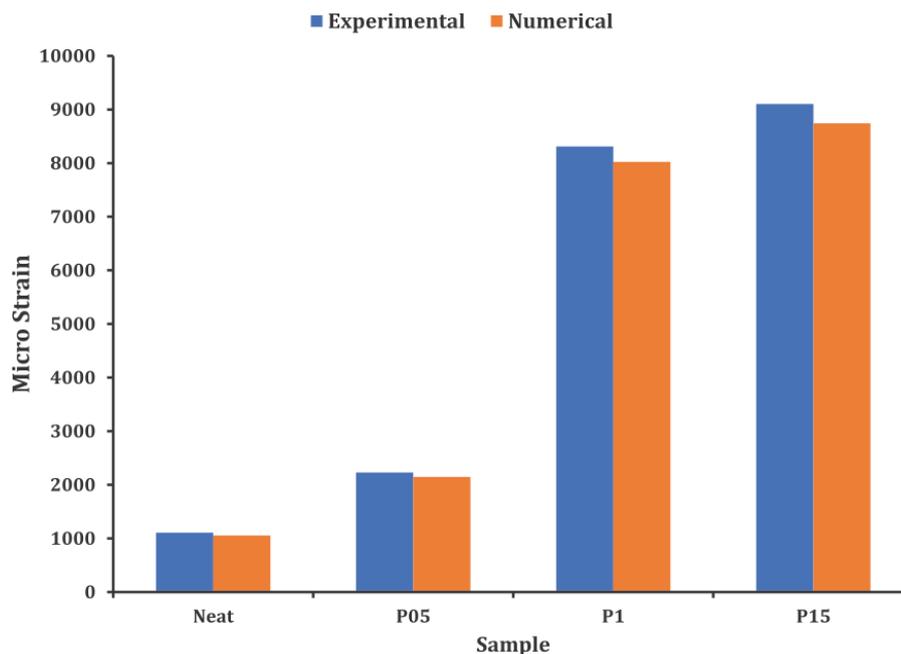


Figure 5. Micro strain of experimental and numerical approach for number of cycles of 10000

Figure 5 shows results of numerical model with experimental test results. As it can be seen in this figure, using linear viscoelastic parameters of asphalt binder and then extending these parameters to asphalt mastic and asphalt mortar phase, it is possible to predict fatigue behaviour of asphalt mixtures. The numerical models are run for 10000 cycles due to calculation cost and limitation of running time in this research. However, it can simply be done to increase number of cycles for numerical running and compare experimental results with numerical ones.

5. Conclusion

This paper, investigates the effect of PPA modifier on fatigue performance of asphalt binder and mixture including experimental tests and numerical simulation. The experimental program includes frequency sweep test using DSR at 25°C for all asphalt binder and also indirect tensile fatigue (ITF) for all specimens of asphalt mixture. On the other hand, the aggregate skeleton of the bituminous composites was performed using MOA software to generate random inclusions of various sizes and shapes.

The experimental results of asphalt mixture indicated that adding PPA improve the fatigue behaviour of asphalt mixtures at moderate temperatures. According to the experimental result, the dosage of 1% was obtained as the optimum percentage of asphalt binder modifier. On the other hand, the numerical model results approve the experimental outcomes by considering the generalized Maxwell model which applied in this model. So, it can be concluded that numerical simulation has shown a good agreement with experimental results.

6. References

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