Jurnal
Teknologi

Full paper

Performance of Modified Asphalt Binder with Tire Rubber Powder

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Article history

Received : 5 September 2014
Received in revised form :
3 December 2014
Accepted : 3 January 2015

Graphical abstract

Abstract

The two major distresses associated with flexible pavement are rutting deformation and fatigue cracking in world highways. This is mainly because of the increasing load and higher tire pressure of vehicles which are applied to highway pavements today. At the same time, the asphalt containing neat binders does not always performed as expected. As a consequence, these distresses reduce the design life of the pavement and increase the maintenance costs tremendously. Therefore, in order to minimize the distresses and increase the durability of asphalt pavement, there is need to improve the performance properties of neat asphalt binders. Many researchers reported that using different types of polymer to modify the asphalt binder could be a solution to minimize the distresses occurred in asphalt pavement and improve the overall performance of the pavement. Disposal of waste tires is a serious environmental concern in many countries. Several attempts were made in the past to modify asphalt binder using tire rubber powder to improve the performance of neat asphalt binders. It is believed that the use of Tire Rubber Powder (TRP) as an additive in the modification of asphalt binder can improve the binder performance properties, increase the durability of the pavement, and reduces the waste disposal problem. This study aims to review the previous studies conducted on the use of tire rubber powder in the modification of asphalt binder. It was observed that addition of tire rubber powder to the asphalt binder enhances the properties of modified binder. It was found that an increase in the percentage of tire rubber powder causes an increase in rutting factor ($G^*/\sin\delta$) and decrease in fatigue factor ($G^*\sin\delta$) indicating higher resistance against rutting and fatigue cracking. In addition, the use of tire rubber powder to modify asphalt binder is considered as a solution to enhance environmental and economic sustainability of pavements.

Keywords: Modified asphalt binder, tire rubber powder, rutting, complex shear modulus G*, sustainability, dielectric constant

■1.0 INTRODUCTION

Asphalt pavements are designed to resist rutting, fatigue cracking, low temperature cracking and other pavement distresses. Rutting and fatigue cracking are very known to be the most common distresses that occur in asphalt pavement. The rutting deformation occurs at high temperature, and fatigue cracking occurs at intermediate and low temperatures. These distresses reduce the design life of the pavement and increase the maintenance costs. This is due to the rapid growth of traffic volume and vehicle loads which led to the performance of neat asphalt binders unsatisfactory for paving applications[1]. To minimize the structural damage of asphalt pavement and increase the durability of the pavement, the neat asphalt binder needs to beimproved with regards to performance properties such as resistance against rutting and fatigue cracking[1-2]. The use of polymers to modify the asphalt binders is considered as one of the promising options to lessenthis problem and suggested to improve the properties of the binder.

Besides, the physical and chemical properties of bitumen binder, it possess a unique and fundamental microwave properties and its microwave permittivity value ranges from 2 to 7 depending on the grade of bitumen[3].

The modification of asphalt binder involving polymer additives such as styrene butadiene styrene (SBS) and styrene-butadiene rubber (SBR), etc. began in the United States, in the1980s due to increasing load and pressure of vehicles tires applied to the pavements [4]. However, the high cost of these polymers (SBS and SBR) compared to asphalt binder means that the amount of polymer needed to improved pavement performance should be as small as possible. The use of recycled polymers (such as tire rubber powder) appears attractive and promising because of their successful performance as well as environmental and economical advantages [5].

Disposal of waste tires is a serious environmental concern in many countries. About 280 million scrap tires were generated annually in the United States[6]. While the number of scrap tires has increased, available disposal spaces havedeclined. This scrap tires problem has become a major issue in the past years as the number of scrap tires has steadily increased. One beneficial method to utilize scrap tires is to use tire rubber powder of using tire rubber powder modified asphalt binders in pavement construction. These include improved performance properties, increasing rutting and fatigue resistance, and, reducing temperature susceptibility. From an environmental and economic perspective, the use of waste tire rubber powder in the modification of asphalt binder will be environmentally beneficial and result in greater cost savings [7-9].

■2.0 BACKGROUND OF TIRE RUBBER POWDER AS MODIFIER IN ASPHALT PAVEMENT

The earliest experiments involved incorporating natural rubber with bitumen in the 1840s to increase its performance properties [10]. The concept of utilizing scrap tire rubber in asphalt pavement was initially developed in 1950 for use in asphalt surface treatments 1950 [11].According toHuffman[12], a material engineer in Phoenix, Arizona, experimented with adding ground tire rubber to hot liquid asphalt. They found that after thoroughly mixing crumb rubber with asphalt binder and allowing it to blend for periods of 45 to 60 minutes, new material properties were produced. In the 1970s, the use of Crumb Rubber Modifier (CRM) in Hot Mix Asphalt (HMA) expanded and has continued to evolve since the CRM binders provide enhancedperformance of asphalt mixtures, including increased resistance to permanent deformation and thermal and fatigue cracking [10]. In the mid-1980s, the Europeans began the development of newer polymers and additives for use in asphalt binder modification [13]. Nowadays, the use of tire rubber powder from scrap tires as modifier in asphalt binder has developed interest and has shown that tire rubber powder can improve the properties of the binder by reducing the binder’s inherent temperature susceptibility [14].

2.1 Tire Rubber Powder Manufacturing Process

Tire rubber powder also known as crumb rubber is produced by shredding and grinding scrap tires into very small particles. In the process, most of the steel wires and reinforcing fibers of the recycled tires are removed. The ambient and cryogenic processes are the two main methods normally used to produce tire rubber powder[14]. Ambient grinding can be classified in two ways: granulation and cracker mill. A granulator shreds and cuts the tire material with revolving steel plates into cubical, uniformly shaped particles with sizes ranging from 9.5mm to 0.425 mm. The cracker mill passes the material between rotating corrugated steel drums to produce irregular, elongated, torn particles with sizes ranging from 4.75 mm to 425micron (No. 40 sieve). Finer crumb rubber (smaller than No. 40 sieve) can be produced with the micro mill[15]. In the cryogenic process, the tire chips are crushed after being subject to freezing conditions using liquid nitrogen until it becomes brittle, and then cracking the frozen rubber into smaller particles with a hammer mill. The cryogenic process is a bit faster operation resulting in production of fine sieve size. Each process can produce crumb rubber of similar particle size, but the primary difference between them is the particle surface texture. Crumb rubber particles produced by the ambient process have an irregular shape with a rough texture due to the shredding action of the rubber particles. The crumb rubber particles resulting from the cryogenic process have smooth surfaces. This difference inparticle surface texture results in the ambient particles havinghigher surface area than the cryogenic crumb rubber [14, 16]

Figure 1 Scrap tires[3]

Figure 2 Tire rubber powder [3]

Figure 3 Rutting deformation [3]

Figure 4 Fatigue cracking [3]

2.2 Tire Rubber Modified Asphalt Binder

The addition of polymers usually has the effect of increasing the stiffness of the binders at high service temperatures without increasing the stiffness at low service temperatures. This modification of binder properties means that the asphalt could be more rut resistant at high service temperatures while its cracking resistance at low temperatures would not be lessened. Tire rubber powder is one of the commonly used binder additives for this purpose.The tire rubber powder modified asphalt binder provide improved mechanical properties, increasing pavement durability, and enhance fatigue resistance [7]. According to study by Mashaan et al. [17], the addition of tire rubber powder to the asphalt binder enhances the physical and rheological properties of modified asphalt binder. In addition, the tire rubber powder modified asphalt binder has become more popular because of its reported advantages including increased pavement life, reduced maintenance cost, decreased pollution and increased environmental quality[18-21].

■3.0 PHYSICAL PROPERTIES OF TIRE RUBBER POWDER MODIFIED ASPHALT BINDER

3.1 Penetration Properties

Penetration measures the consistency of asphalt binder. The addition of tire rubber powder to the asphalt binder decreases the penetration value. The higher the percentage of tire rubber powder in the mix, the lower the penetration values, indicating that the binder becomes harder and more consistent [17, 19, 22]. Ali et al. [24], investigated the properties of aged rubberised asphalt binder of 80/100 penetration grade with different percentage of tire rubber powder[24]. The results of penetration values of neat and modified asphalt binder decreased after both aging conditions of Rolling Thin Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV). Also, the modified asphalt binders have lower penetration values than neat binders.

3.2 Softening Point Properties

Softening point measures the consistency of asphalt binder, which represents the temperature at which a change of phase from solid to liquid occurs. The addition of tire rubber powder to asphalt binder increases the softening point value, and as the TRP percentage increase the softening point also increases as the binder becomes increasingly viscous [17, 22]. According to study by Ali et al. [24] the softening point values of neat and tire rubber powder modified asphalt binder increased after both aging conditions of RTFO and PAV, as the TRP percentage increased.

3.3 Viscosity Properties

The viscosity of asphalt binders at high temperatures is an important property as it reflects a binder's ability to be pumped through an asphalt plant, thoroughly coat theaggregate in a hot mix asphalt (HMA) mixture, and beplaced and compacted to form a new pavement surface. The viscosity increases on addition of tire rubber powder to the asphalt binder [17, 22]. Modified asphalt binders are normally more viscous than neat binders [23]. Ali et al. [24] conducted a research on the effect of aging on the properties of rubberised asphalt binder. Results showed that the higher percentage of TRP led to the higher viscosity of the tire rubber modified binders. The viscosity of neat and modified asphalt binder increases after both aging conditions of RTFO and PAV. Also, the increase in percentage of tire rubber powder has a great effect on aged rubberised asphalt binder viscosity than aged unmodified binder. The viscosity is a continuously increasing non linear function of tire rubber percentage and the relative increase is a factor related to the temperature application [25].

3.4 Rheological Properties of Tire Rubber Powder Modified Asphalt Binder

The study onrheological properties of asphalt binder is an important phenomenon to characterize the dynamic mechanical behavior of binders. Asphalt binder is a thermoplastic, viscoelastic material and behaves as glass-like elastic solid at low temperature or during high loading frequencies and as viscous fluid at high temperatures or low loading frequencies. The thermal and mechanical deformation of asphalt binder can be defined by its stress-strain-time and temperature response. Deformation and flow of the asphalt binder is important in determining pavement performance. Pavements that deform and flow too much may be susceptible to rutting and bleeding while those that are too stiff may be susceptible to fatigue or thermal cracking. Pavement deformation is closely related to asphalt binder rheology [26].

■4.0 EXPERIMENTAL

4.1 Dynamic Shear Rheometer (DSR)

The Strategic Highway Research Program (SHRP) recommended new binder testing equipment to measure the physical and/or rheological properties of modified as well as unmodified asphalt binders that can be related directly to field performance by engineering principles.Among the equipment, the Dynamic Shear Rheometer (DSR) was chosen to evaluate permanent deformation and fatigue cracking resistance characteristics by measuring the properties of asphalt binder at high and intermediate temperatures, respectively [27].DSR is used to characterize the viscoelastic behavior of asphalt binders at intermediate and high service temperatures [23]. Asphalt binder rheology can broadly be represented by two main viscoelastic parameters: complex shear modulus and phase angle[28]. These parameters change with temperature and loading time. The DSR measures a specimen's complex shear modulus (G*) and phase angle (δ) over a temperature range from 30°C to 80°C, which are indicators of an asphalt's resistance to shear deformation in the viscoelasticregion, and help predict the rutting potential and fatigue life of hot mix asphalt pavements.

4.2 Complex Shear Modulus (G*) and Phase Angle (δ)

The complex shear modulus (G*) is defined as the ratio of the peak stress to the peak strain which measure the overall resistance to deformation of a material when repeatedly sheared, while the phase angle (δ) is the phase difference between the applied stress and the resulting strain. It represents the relative distribution between the elastic response and the viscous response to loading of the asphalt binder [29].

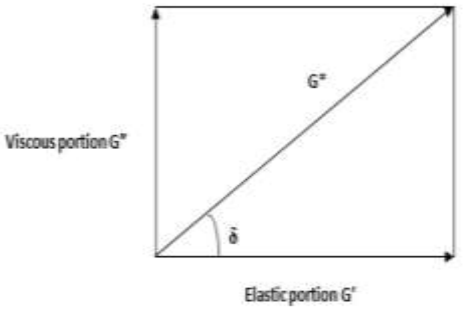

Figure 5 Viscoelastic properties of bitumen binder.

The complex modulus consists of the storage modulus (G') and the loss modulus (G"). The storage modulus, which is the elastic (recoverable) component, represents the amount of energy stored in the sample during each loading cycle. The loss modulus, which is the viscous (non-recoverable) component, represents the amount of energy lost during each loading cycle. When the phase angle is zero degrees, elastic behavior, the complex modulus consists solely of the storage modulus. Likewise, when the phase angle is 90 degrees, viscous behavior, the complex modulus consists solely of the loss modulus. It is therefore necessary to determine both the complex modulus and the phase angle within the viscoelastic range of response to adequately characterize asphalt binders [30]. The graphical description of the phase angle with respect to the complexmodulus is shown in Figure 5.

Elastic component, G*cosδ is recoverable, whereas, G*sinδ is not recoverable. G*sinδ is responsible for fatigue cracking, G* / sin δ is responsible for rutting.The addition of tire rubber powder to the asphalt binder has an obvious effect on the binder rheology by increasing in the complex shear modulus G* and decrease in the phase angle δ. The complex modulus increases with increase in percentage of tire rubber powder [17]. According to Singh and Kumar [22] and Ali et al. [24], there is a constant increase in complex modulus, G*, with increase in percentage tire rubber powder after aging. The increase in complex modulus (G*) and decrease in phase angle (δ) of the modified asphalt binder indicate higher resistance to deformation as compared to neat asphalt binder.

4.3 Rutting Factor(G* / sin δ)

Permanent deformation (rutting) is one of the major distresses causing failures of asphalt pavements. Heavy truck traffic, increased wheel loads, and use of high pressure radial tires have aggravated the global problem of rutting failure of asphalt pavements [31-32].The relationship G*/sinδ was chosen as the parameter for SHRP specifications with respect to rutting [25]. It is used as an indicator for rutting resistance in the currentUS superpave specifications. The Superpave binder specification requires the rutting factor, G*/sinδ to be a minimum 2.20 kPa for RTFO aged binder and 1.0kPa for unaged binder. The rutting factor reflects the total resistance of a binder to deform under repeated loading (G*), and the relative energy dissipated into non-recoverable deformation (sinδ) during the loading cycle. A higher value of G*/sinδ implies that the binder behaves more like an elastic material, which is desirable for rutting resistance[33]. The rutting resistance was evaluated mainly by examining G*/sinδ values of RTFO aged binder, because the aging simulates a short-term aging, including the hardening at the asphalt plant. Generally, the higher G*/sinδvalues indicate that the binders will be less susceptible to permanent deformation at high pavement temperatures [34-36]. The addition of tire rubber powder to asphalt binder increased the values of G*/sinδand could improve the resistance against rutting[14, 17]. The rutting factor, G*/sinδof the neat and TRP modified asphalt binder was measured at 76°C for different rubber percentage. The higher TRP percentage resulted in the better rutting resistance properties. The rutting resistance was found to increase with increase in the percentage of TRP after RTFO Aging [24].Cooley et al. [2]investigated the effect of aging on the rheological properties of tire rubber modified asphalt binder. Three percentages of fine grain tire rubber passing 40-mesh sieve, namely 3%, 9% and 15% by weight of asphalt binder were blended with 80/100 penetration grade asphalt binder. The blending was done at 150°C and a speed of 250rpm for blending time of 2hr. Result showed that aging influences asphalt binder rheology significantly, by increasing complex shear modulus (G*) and decreasing phase angle (δ). This indicated a good performance of adding the tire rubber powder to the asphalt binder.

4.4 Fatigue Factor(G*sinδ)

Fatigue cracking is considered to be one of the most significant distresses modes in asphalt pavement due to repetitive traffic loading over time which occur at intermediate and low temperatures and can be accelerated by pavement aging [37]. The relationship G*sinδ was chosen as the parameter for SHRP specifications with respect to rutting fatigue cracking. It is used in the current SUPERPAVE (SUperior PERformance Asphalt PAVEment) specifications as an indicator for fatigue cracking resistance. The Strategic Highway Research Program (SHRP) had a maximum value of 5000 kPa for G*sinδ, and low values of G*sinδ are considered desirable attributes from the standpoint of resistance to fatigue cracking [38-42]. A lower value of G*sinδ means a lower potential of fatigue cracking. This can be explained by the fact that as G* decreases, the asphalt binder becomes less stiff and is able to deform without building up high stresses, and as δvaluedecreases, the asphalt binder becomes more elastic and hence can regain its original condition without dissipating energy [25]. Since the asphalt binder becomes stiffer due to aging during its service life and becomes more susceptible to cracking, the DSR test for fatigue factor determination is conducted on PAV-aged samples.

The use of tire rubber powder modified with asphalt binder seems to enhance the fatigue resistance, as illustrated in number of studies [43-44]. Lee et al. [14]investigated the effect of CRM with different percentages (0, 5, 10, 15, and 20% by weight of asphalt binder) on rutting and fatigue cracking performance of modified asphalt binder. After PAV aging, the fatigue resistance parameters, G*sinδ values, of the neat and CRM binders were measured using the DSR at 25^{0}C and the results illustrated that, the higher CRM percentages seemed to lead to the lower G*sinδof the CRM binders. A study conducted on the rheological properties of aged rubberised asphalt binder by Ali et al. [24], the fatigue resistance parameter, G*sinδ values, of the unaged asphalt binder and rubberised binders after pressure aging vessel (PAV) measured using the dynamic shear rheometer (DSR) at 31°C showed that increase in tire rubber powder percentage has an obvious effect on aged rubberised asphalt binder fatigue parameter, G*sinδ, with correlation coefficient R^2= 0.816.Also, G*sinδ of the modified asphalt binder is lower than the unmodified binder at temperature of 31°C, indicating that rubberised asphalt binder would improve the fatigue resistance of asphalt binder as a result of addition of tire rubber powder as modifier.

4.5 Effect of Rubber Concentration

Lee et al. [14] conducted a study on the effect of crumb rubber on the performance properties of rubberized binder in HMA. The results showed that the higher crumb rubber percentages the increase in the viscosity at 135°C and improved rutting and fatigue cracking properties. It was also noticed that increased in crumb rubber percentage led to an increase in softening point, elastic recovery, resilience and decrease in ductility and penetration at 25°C as reported by a number of studies[17, 22, 24]. Another study by Ali et al.[24] on the rheological properties of aged rubberized asphalt binder. Results showed that after RTFO at 76°C and PAV at 31°C, higher crumb rubber percentage led to an increase in rutting factor (G*/sinδ) and fatigue factor (G*sinδ) which indicated a higher resistance to rutting and fatigue cracking.

4.6 Effect of Blending Conditions

According to Asphalt Institute blending and paving temperatures can be based on asphalt binder viscosity conducted at 135°C and 165°C. The binder temperatures corresponding to 170 and 280 centipoises are taken as the blending and paving temperature of the asphalt binder. Generally, asphalt binders and tire rubber powder are blended together at their blending temperatures for different blending time. These two factors influence the performance properties of tire rubber modified asphalt binder. The time and temperature used to blend the components can affect the consistency of rubber modified asphalt binder and thus, must be cautiously used in order to achieve successful product[17].Another study by Mashaan et al. [17]found that there was significant effect for blending time of 30 and 60 minutes on rheological properties of rubber modified asphalt binder.

■5.0 CONCLUSION

This paper aims to review the previous studies conducted on the use of tire rubber powder to modify asphalt binder. Based on the results of previous studies, the performance properties of modified asphalt binder are improved with the addition of the tire rubber powder. Also, an increase in the percentage of tire rubber powder causes an increase in G*/sinδ and decrease in G*sinδ indicating a higher resistance against rutting and fatigue cracking. From the environmental and economic standpoint, the use of tire rubber powder as an additive in modified asphalt binder would contribute to alleviating pollution problems caused by discarding waste tire rubbers and has the potential to be cost effective.

Acknowledgement

The support provided by Malaysian Ministry of Higher Education and Universiti Teknologi Malaysia in the form of a research grant (Vote No. 09H33) for this study is very much appreciated.

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