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Value-added application of waste PET based additives in bituminous mixtures containing high percentage of reclaimed asphalt pavement (RAP)

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A B S T R A C T

The use of reclaimed asphalt pavement (RAP) in road pavement construction has been widely encouraged due to its environmental and economic benefits. However, the percentage of RAP is usually capped at low percentages as studies have shown that a high percentage of RAP might be detrimental to overall pavement performance. Recent research has shown that the addition of waste plastic materials such as Polyethylene Terephthalate (PET) or their functionalized additives into asphalt pavement may potentially improve the durability of pavement and also help alleviate the environmental problems caused by plastic. The main objective of this study is to investigate the feasibility of using the additives, derived from waste PET through an aminolysis process, to improve the performance of bituminous mixtures containing RAP, by characterising the binder properties. To achieve this objective, binder samples composed of virgin bitumen, aged bitumen at various percentages, and PET derived additives, were prepared. These samples were then characterized through various laboratory tests, including dynamic shear rheometer, bending beam rheometer, moisture susceptibility, infrared red spectroscopy and fluorescence microscopy tests. The results indicated that the samples containing RAP and PET derived additives provided better overall performance compared to the conventional binder, increasing the rutting resistance by at least 15% and fatigue cracking resistance by up to 60%. Usage of such waste PET based additives as an additive for RAP mixtures represents an approach to deal with a relevant recycling problem while simultaneously recovering two value-added materials.

1. Introduction

The inclusion of waste materials such as reclaimed asphalt pavement (RAP) in pavement mixtures has become increasingly common due to numerous environmental and economic benefits. Practitioners around the world are constantly assessing the advantages of allowing higher percentages of RAP in pavement while also maintaining the highest performance standards to meet the increasing demands and regulations (Al-Qadi et al., 2007). Many transport authorities and departments have limited the maximum amount of RAP used in surface layers, certain mixtures types and in some cases large or critical projects. The amount of RAP used in surface layers was usually less than 15 percent initially as there was no significant advantage economically for using a larger percentage of RAP. In 2006 and also in 2008, there was a sharp increase in asphalt binder costs and reduction of supplies, hence using a greater percentage of RAP became a priority again (NCDOT, 2007). RAP has usually undergone years of natural ageing and the binder that is present in RAP is aged and harder. Hence, the incorporation of this aged binder to virgin HMA material results in a modified mix that is potentially also harder (McDaniel and Shah, 2003). While this may enhance certain performance properties such as rutting resistance, it also raises significant concerns over fatigue cracking and moisture damage performance (MTO, 2008). Additionally, there are also concerns over RAP mixture design especially in regard to the amount of RAP binder that is mobilised in a mixing plant or in the mix design process. Although it is regarded that complete mobilisation and blending is unlikely for traditional asphalt mixtures, it is recognized now that a considerable amount of mixing occurs. RAP mixtures behave as a composite of both the RAP and virgin binders (Sreeram et al., 2018). Due to these limitations, it is now common that RAP mixtures are used in conjunction with other

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bitumen modifiers such as rejuvenators and antistripping additives to improve their rheological properties and provide a more balanced performance. Many of these commonly used modifiers are polymeric in nature and their incorporation in RAP mixtures are known to enhance their rheological properties (Hagos et al., 2012). The main objective of this study is to develop polymeric additives through the chemical recycling of waste PET to improve the performance of mixtures containing RAP.

2. Polymer modification in RAP mixtures

Currently, there is an increase in the usage of polymer modified bitumen modified bitumen in road pavement and highways as they offer considerable advantages over conventional bitumen such as lower susceptibility to temperature variations and higher resistance to deformation at elevated pavement temperatures (Yildirim, 2007). The addition of these polymers such as styrene–butadiene–styrene (SBS), ethyl vinyl acetate, polyvinyl chloride, polyethylene, polyoctenamer, polyethylene terephthalate (PET) materials in asphalt pavement has now been widely studied and its benefits extensively established. The use of polymers in asphalt binders generally improves the deformation performance of HMA mixes (Kim et al., 2014), however when polymers are used in conjunction with RAP, the behaviour of the resulting mix can vary considerably depending on the type of polymer that is used. Published literature has indicated mixed results when considering the use of RAP with polymers. It has been indicated that at lower levels of polymer modification the addition of RAP results in increased rutting resistance while at higher levels of polymer modification the addition of RAP does not have a significant effect on the rutting resistance of the HMA mix (Kodippily et al., 2017). The main limitation of using RAP in HMA is the low temperature cracking performance due to additional stiffness of the combined mixture. Polymer modification has been extensively used to improve the cracking performance of HMA mixes where the presence of polymers enhances the elastic properties of asphalt binder thus improving the bond strength between the materials and prolonging the service life of the pavement. Overall, polymer modification has been shown to reduce the low temperature cracking susceptibility of HMA mixes while enhancing the fatigue performance, hence making it suitable to be incorporated into RAP mixes to improve its performance properties (Mogawer et al., 2011). Polyethylene Terephthalate (PET), a thermoplastic polyester which constitutes 18% of the total polymer produced worldwide (Ji, 2013) and commonly used to make plastic bottles is used as the polymeric additive in this research. The large-scale use of PET for manufacturing of plastic material in various forms including bottles has made it a major cause for environmental pollution. This material has also been known to transport persistent organic pollutants such as polychlorinated biphenyl (PCB) which can have negative effects on the environment. The slow rate of decomposition of PET and its non-bio degradable nature has led to scientists looking into ways to recycle it. Currently, both chemical and physical methods have been employed to recycle PET however chemical recycling has the advantage of leaving the polymer to produce several industrially useful products and eliminating the practice of disposal of PET in landfills. Since PET recycling has not been carried out in the same amount as its production; it would be worthwhile to find out new application areas for PET bottle wastes to maximize their end-of service life management effectiveness (Sarker and Rashid, 2013). The usage of waste PET as an additive for asphalt road pavement material has been studied previously although it can still be regarded to be at an early stage. In prior studies, PET waste was generally added to the asphalt mixture with dry process or used as aggregate in the asphalt mixture in order to improve the resistance to permanent deformation, Marshall Stability, stiffness and fatigue life of road pavement (Ahmadinia et al., 2011; Moghaddam et al., 2014). However, phase separation and a decrease in specific gravity of the asphalt mixtures have been reported due to the inhomogeneous distribution of PET in asphalt (Ameri and Nasr, 2016). Apart from this, asphalt was modified with a number of additives derived from PET waste by aminolysis and glycolysis reaction as a wet process and found to improve the Marshall Stability and moisture resistance depending on the asphalt and additive contents (Padhan et al., 2013; Gürü et al., 2014). These initial studies have indicated that the PET additives have significant potential to improve the stripping characteristics and overall performances of asphalt mixtures. It is likely that PET additives could act similar to commercial rejuvenating agents and hence would be suitable to be incorporated into high RAP mixes to improve moisture damage, fatigue cracking and low temperature performance properties. The combined use of waste plastic and reclaimed asphalt pavement could also open a new chapter in the efficient disposal of products currently landfilled and help alleviate the pressure of disposal. In this study, Triethylenetetramine (TETA) was utilised for the aminolysis of waste PET into an additive for bitumen modification. Subsequently, the modified binders were tested for various performance parameters to evaluate their rheological properties.

3. Material preparation and research methodology

3.1. Material preparation

3.1.1. Poly (ethylene terephthalate) (PET)

The waste PET water bottles were collected after proper identification. The PET bottles were stripped of all labels and cleaned with normal detergent solution followed by proper washing and drying to remove any potential contaminants. The bottles were then cut into small pieces about 5 mm by 5 mm and dried at 80 °C temperature for 4 h.

3.1.2. Extraction of aged binder from reclaimed asphalt pavement (RAP)

The reclaimed asphalt pavement (RAP) was obtained from the Highways Department, Hong Kong. It was obtained by 10 mm wearing course cold milling and was reported to be of low to moderate ageing level. The RAP binder was extracted using the solvent extraction method as per AASHTO T164.

3.1.3. Synthesis of PET additive

The PET waste was used as a synthon and chemically converted through a non-catalytic route into benzamide derivatives through an aminolysis process (Leng et al., 2018). A three necked 500 ml round bottomed flask equipped with a heating mantle, overhead stirrer, water condenser, nitrogen gas sparging tube and a thermos well pocket containing a thermometer was charged with 30 g of PET and excess triethylenetetramine (TETA) in the presence of nitrogen gas. The mixture was heated at 130 °C–140 °C to reflux for 2 h. The solution turned homogeneous as the PET degradation completed. At the end of the reaction, the polyamines and glycols are recovered under vacuum. The resulting product is a residue recovered in quantitative yields at ambient temperatures (Figs. 1 and 2).

3.2. Characterization of PET additives

The PET degradation was confirmed by IR analysis which showed the disappearance of ester group peak at 1735 cm^{-1} and the formation of amide peaks at 1637.6 cm^{-1} and 1544.4 cm^{-1},