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Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes

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ABSTRACT

Nowadays, the use of recycled waste materials as modifier additives in asphalt mixes could have several economic and environmental benefits. The main purpose of this research was to investigate the effect of waste plastic bottles (Polyethylene Terephthalate (PET)) on the stiffness and specially fatigue properties of asphalt mixes at two different temperatures of 5 and 20 °C. Likewise, the effect of PET was compared to styrene butadiene styrene (SBS) which is a conventional polymer additive which has been vastly used to modify asphalt mixes. Different PET contents (2–10% by weight of bitumen) were added directly to mixture as the method of dry process. Then the resilient modulus and fatigue tests were performed on cylindrical specimens with indirect tensile loading procedure. Overall, the mix stiffness reduced by increasing the PET content. Although stiffness of asphalt mix initially increased by adding lower amount of PET. Based on the results of resilient modulus test, the stiffness of PET modified mix was acceptable and warranted the proper deformation characteristics of these mixes at heavy loading conditions. At both temperatures, PET improved the fatigue behavior of studied mixes. PET modified mixes revealed comparable stiffness and fatigue behavior to SBS at 20 °C. However, at 5 °C the fatigue life of SBS modified mixes was to some extent higher than that of PET modified ones especially at higher strain levels of 200 microstrain.

1. Introduction

During the recent years, engineers have been looking for new environmental friendly techniques in construction of roads pavement and much studies have been devoted to this research field (e.g. utilizing recycled asphalt pavement (RAP) materials, crumb rubber, construction debris, etc.) [1–3]. During the service life, many external factors might deteriorate the integrity of pavement. Among these factors, traffic loading is considered as the main factor which finally leads to fatigue cracking and permanent deformations especially in upper pavement layers. There are vast majority of cases which addressed the fatigue properties of conventional or modified asphalt mixes. Effects of many parameters and additives have been studied in this regard [4,5]. Different additive materials including fibers and polymers have been used to improve the fatigue resistance of asphalt mixes. Most of these materials were found to be effective with beneficial effects on the fatigue behavior of asphalt mixes [6–10].

The main reason of incorporating polymer modifiers in bitumens is to extend the range of service temperature or reduce the temperature sensitivity of them. These binders are visco-elastic materials. The degree to which their behavior is viscous or elastic is a function of temperature, loading period and loading duration. At high temperatures or long loading times, they behave like viscous liquids whereas at low temperatures or short loading times they behave as elastic (brittle) solids. Under intermediate conditions of the service period, they exhibit viscoelastic behavior in which the material's response will be dependent upon temperature or loading velocity. For a polymer to be effective in road applications, it should be blend with bitumen and improve its efficiency at service temperatures without making it too viscous at mixing temperatures or too brittle at low temperatures. In other words, it must extent the range of service temperature while it improves the overall performance of pavement.

Polymers that have been used for asphalt mix modification can be divided into three groups including thermoplastic elastomers (e.g. styrene butadiene styrene (SBS) and crumb rubber (CR)), plastomers (e.g. ethylene vinyl acetate (EVA) and polyethylene (PE)) and polymers with chemical reaction [11–13].

Thermoplastic elastomers such as SBS are usually used to extend both minimum and maximum service temperatures of

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bitumen, whereas plastomers are well known as effective additives at high service temperatures [11,12].

Although, the use of polymer modifiers has been recognized as an appropriate solution for promoting the engineering properties of bitumen and asphalt mixes, but it is relatively a costly procedure for paving roads [14,15]. From an environmental and economic point of view, the use of recycled instead of virgin materials could have several advantages such as help easing landfill pressures and reducing demands of extraction from natural quarries. Furthermore, this would be an alternative solution for environmental pollution by utilizing waste materials as secondary materials in road construction projects. As published in the literature, the waste of glass, rubbers, plastics and mineral productions were some popular materials used to modify the properties of bitumens and asphalt mixes [16]. Most researches have focused on using waste additives to improve the deformation and fatigue characteristics of asphalt mixes. According to research results, waste glass and waste rubber had a considerable contribution to fatigue resistance of these mixes [17,18].

Nowadays, many countries are seriously encountered with problems related to waste plastic materials. Plastic materials such as plastic bottles are mainly composed of Polyethylene Terephthalate (PET) polymer. PET is a thermoplastic polymer resin of the polyester family and is used in synthetic fibers, beverage, food and other liquid containers, thermoforming applications and engineering resins often in combination with glass fiber [19]. PET is produced by the polymerization of ethylene glycol and terephthalic acid. Ethylene glycol is a colorless liquid obtained from ethylene, and terephthalic acid is a crystalline solid obtained from xylene. When heated together under the influence of chemical catalysts, ethylene glycol and terephthalic acid produce PET in the form of a molten, viscous mass that can be spun directly to fibers or solidified for later processing as a plastic.

Based on previous studies PET has a great potential to be reused as modifier in asphalt mixture. Results indicated that adding PET to asphalt raised the mix resistance against permanent deformation and rutting [20,21]. During a laboratory study Mahrez & Karim examined the effect of different PET contents on the rheological properties of modified bitumen. They found that addition of PET to bitumen will increase the viscosity and reduce the temperature susceptibility of modified bitumen. Furthermore, the PET modified bitumen showed preferable elastic properties than the original one (i.e. higher complex modulus and lower phase angle) [22]. During a laboratory study about stone matrix asphalt (SMA) mixes the effect of PET was investigated using the cylindrical specimens. It was inferred that incorporating PET will reduce the bitumen loss which is one of the main SMA deficiencies. Furthermore, the effect of PET on the moisture susceptibility of these mixes was found to be negligible [23]. In a 2012 study Moghaddam et al. compared the stiffness and fatigue properties of PET modified mixes with conventional asphalt. Based on their report the fatigue life of modified mix containing 1% PET (by weight of aggregate) was twice than that of unmodified mix. However, the stiffness of modified mix was to some extent lower than conventional mix. The outcomes of this research indicated that the application of PET in SMA mixes could meet the various requirements of different environmental and loading conditions. Especially the results of stiffness test warranted the proper deformation characteristics of modified mixes at heavy loading conditions [24].

The addition of thermoplastic polymers (e.g. PET) to bitumen or asphalt mix enhances the material rigidity and restricts the permanent deformations under heavy loading conditions especially in upper pavement layers at higher temperatures [25]. The beneficial effects of PET on such high temperature characteristics of asphalt mixtures have been proved elsewhere [22,24]. However their performance in increasing the bitumen elasticity during drastic and sudden temperature drops is not always satisfactory. In fact they might deteriorate the intermediate and low temperature characteristics of bitumen and asphalt mix (i.e. increasing the cracking potential of mix) [25].

Apart from abovementioned investigations, there is not enough information regarding to fatigue properties of PET modified mixes. For example the fatigue response of these mixes at various temperatures has not been well established. Since extending the range of service temperature is the main purpose of bitumen and asphalt modification it will be interesting to investigate the fatigue properties of PET modified mixes at various temperatures.

Hence, in this study, the fatigue and stiffness properties of PET modified mixes have been investigated at intermediate and low temperatures. In this regard the effect of PET was compared with SBS which is a conventional polymer modifier in asphalt mixes and most of earlier researches have proved the beneficial effects of this additive on the technical characteristics of asphalt mixes [12,21,25].

The main objectives of this research were as follows:

- To investigate the effects of PET on stiffness properties of modified mixes at two testing temperatures.
- To evaluate the fatigue behavior of PET modified mixes in comparison with unmodified asphalt mixes.
- To compare the stiffness and fatigue properties of PET modified mixes with that of modified with SBS.

2. Materials and mix design

2.1. Bitumen and aggregate

The original binder used in this study was 60/70 penetration grade bitumen that produced in Tehran oil refinery. Table 1, presents the basic properties of this bitumen. Also, as shown in Fig. 1 a 0–12.5 mm aggregate gradation was selected which was approximately in the middle limit of specifications. Table 2 summarizes the specifications of coarse and fine aggregate fractions and filler materials which were blended to achieve the final gradation.

2.2. Additives

2.2.1. PET

In this study, waste plastic bottle (PET) was used as modifier additive in hot mix asphalt. To this end, PET bottles were cut into small pieces and crushed by a special crusher. Finally crushed particles were sieved to obtain the needed gradation. As indicated by previous researches, desired results were obtained by single size PET particles between the range of 0.425–1.18 mm [23,25]. Hence, in this research, PET chips were crushed and sieved to obtain the above-mentioned dimensions. Fig. 2 shows the image of the PET crumbs after the crushing and sieving process. PET consists of polymerized units of the monomer ethylene terephthalate, with repeating $C_{10}H_8O_4$ units. The related components of studied PET were terephthalic and ethyleneglycol monomers. The physical

Table 1
Technical properties of original bitumen.

Property (unit)	Standard	Value
Specific gravity	ASTM: D70	1.013
Penetration (0.1 mm)	ASTM: D5	65
Softening point (°C)	ASTM: D36	50
Viscosity at 120 °C (cSt)	ASTM: D2170	966
Viscosity at 135 °C (cSt)	ASTM: D2170	467
Viscosity at 160 °C (cSt)	ASTM: D2170	168