Construction and Building Materials 126 (2016) 274–285

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental study on the optimisation of chemical treatment to reduce waste rubber aggregates absorption properties

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HIGHLIGHTS

- This study addresses the absorption properties of waste rubber in bitumen.
- Chemical treatment was devised to improve waste rubber's resistance to absorption.
- An innovative microwave analysis and conventional techniques verified the results.
- Mechanical tests of treated rubber samples showed improvement in their mechanical behaviour.
- Improvements in the mix design are required to achieve a durable surface material.

ARTICLE INFO

Article history:
Received 2 April 2016
Received in revised form 3 August 2016
Accepted 7 September 2016
Available online 20 September 2016

Keywords:
Waste rubber
Scrap tyres
Pavement engineering
Sustainable environment
Chemical treatment
Microwave analysis
Bituminous mix
Bitumen analysis
Mechanical testing

ABSTRACT

Utilisation of abundant waste rubber generated from scrap tyres in pavement engineering applications could be a useful route to consume large extent of the waste from the scrap tyres. It may contribute towards maintaining a greener environment by reducing the associated environmental and social impacts as well as improve the properties of bituminous mixture used for pavement engineering applications. This paper focuses on the upgrading of waste rubber aggregates surface properties by identifying and applying optimised chemical treatment (oxidation and cross-linking). The focus was to increase the life span of bituminous mixtures containing waste rubber as an aggregate by reducing a phenomenon of migration of light fractions (maltenes) from bitumen to rubber which occur at elevated temperatures ranging between 160 and 180 °C. The results of various tests conducted showed the potential of the treatment to reduce the absorption of maltenes into rubber. The existence of the surface treatment was verified through the Scanning Electron Microscope (SEM) analysis of the rubber aggregate. The reduction in the absorption properties of rubber due to the existence of the treatment was verified using the microwave spectroscopy technique. The results of both the tests were promising in terms of indicating the durability of the treatment and the reduction in the absorption properties of rubber. Mechanical tests such as Indirect Tensile Stiffness Modulus (ITSM) and Repeated load axial (RLA) tests were conducted on the newly devised bituminous mix design with 10% of added rubber (by mass of the sample). The results were promising in the case of the aged samples with both the stiffness and load bearing capacity being higher for the aged samples. However, the results need improvement in terms of its applications on the light traffic areas through the replacement of the ordinary filler with the mineral filler. Also, a higher percentage of waste rubber should be added to study the suitability of its use in the flexible surface applications such as children's playgrounds, sports pitches and surfaces, etc.

1. Introduction

1.1. Scrap tyres, their environmental impact and applications

The waste rubber from scrap tyres poses an environmental threat if not utilised efficiently. Since 2006 legislation such as End of Life Vehicles (ELV) salvage, waste incineration and EU directives on the waste landfill management prohibited the disposal of waste tyres arising to the landfill and similar waste disposing routes, etc. [1,2]. Also, stockpiling of the scrap tyres is not allowed because of it being a potential source of fire hazard, cause of environmental damage and other health risks associated with it. It also

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http://dx.doi.org/10.1016/j.conbuildmat.2016.09.021

does add to the disposal costs of the scrap tyres [3–5]. In Europe 95% of the scrap tyres are recycled [6]. The emphasis on recycling the scrap tyres encouraged the introduction of new end use market applications as well as alternative recovery options. Although the market for scrap tyres and its material usage has been established, the amount of tyres that reach their end-of-life cycle worldwide significantly exceeds the end use market of the scrap tyre material. The only exception to this is the UK market of scrap tyres as it is meeting 100% of the recovery target through various routes such as recycling, recovery and reuse [1].

One of the potential applications to utilise a significant number of scrap tyres is to use them in rubberised asphalt pavements surfaces, pavement engineering and flexible rubberised surfaces whereby large quantities of scrap tyres can be consumed. This could potentially reduce the amount of waste generated and can improve some of the engineering properties of the pavements such as fatigue resistance, reduced low temperature surface cracking, improve tensile strength, adhesion, resistance to rutting, elasticity, noise reducing characteristics, safety in wet conditions, flexibility to reduce injuries in the case of playground surfaces, and many more [4,5,7–15].

1.2. Brief problem statement and the literature

Applications of waste rubber aggregates in bituminous mixtures, both in the wet and dry process, resulted in two main problems identified by researchers and professionals [4,5,7–9,11, 16–19]. At elevated temperatures (140–170 °C) the migration of light fractions (constitute resins, aromatics, and saturates) from bitumen to rubber occurs. This causes the swelling of rubber between 3 and 9 times its original size causing it to lose its rigidity and shape. Also, the residual bitumen becomes brittles and hard resulting in the breaking of the bond between the rubber, bitumen and aggregates. This causes the particles of rubber to become loose and become distributed in the bitumen in the case of fine particles (wet process) and on the surface of the pavement leaving gaps on the surface in the case of crumb rubber (dry process). This adversely affects the performance and durability of the surface.

Shakhnazarli [20] has utilised secondary polyethylene, polyamide fibre waste, and crumb rubber to modify bitumen. Airey et al. [7] pointed out the use of modifiers like sulphur, rubbers, thermoplastic polymers, and thermosetting resins to modify the bituminous mixture to improve mechanical properties of the bituminous mix. Stabilising agents such as cellulose and mineral fibres have been used to prevent the drain down [21]. Polymers such as styrene-butadienestyrene (SBS), styrene-butadiene rubber (SBR), Elvaloy, ethylene vinyl acetate (EVA), polyethylene, and others have also been used to modify asphalt binders [22,17]. Frantzis [23] discusses methods to modify rubber including a devulcanization process, heavy paraffinic distillate solvent extract and a water activated method. Additives like Poly phosphoric acid and vestenamer were also used for improving the properties of crumb rubber modified bitumen [24]. Although these treatments, up to an extent, improve the performance in terms of mechanical behaviour and engineering properties (resistance to deformation, low temperature cracking, flexibility, stiffness, etc.) of bitumen and bituminous mixtures that ultimately has an influence on the service life of pavements, the problem of migration of maltenes has not been explicitly addressed by any of the above.

1.3. Waste rubber aggregates treatment

This paper demonstrates the use of suitable chemical additives and their optimised quantities to modify the rubber surface properties to subsequently reduce the migration of maltenes from bitumen to rubber. This could potentially result in a strong adhesive properties of rubber which subsequently helps in improving the bonding between the bitumen and rubber. If successful in reducing the migration of light fraction from bitumen to rubber, the proposed treatment is also expected to improve the resistance to permanent deformation, reduce low temperature surface cracking, and improve the flexibility of the material over a long period of time for the applications such as use in school playgrounds and sports stadiums, shock absorbing surfaces, walkways/pathways, artificial turf for football stadiums. Additionally, it could have potential to be used on light traffic road surfaces [4,5,7–9,11,13,16–19]. A microwave spectroscopy technique was used to analyse the absorption properties of rubber through indirectly studying the properties of bitumen and changes incurred in the spectrum of bitumen after its interaction with the treated rubber. This technique has been demonstrated in previous studies by the same author as this article [25,26] to analyse bitumen properties. The mechanical properties were tested using the Indirect Tensile Stiffness Modulus (ITSM) test and Repeated load axial (RLA) test.

Ateeq et al. [25] and Ateeq et al. [26] attempted to carry out the chemical treatment, however, the optimum chemical treatment parameters were not achieved. This study extends the work by identifying the optimum chemical treatment (percentage of oxidation and cross-linking agents). It also presents the mechanical testing of the bituminous samples prepared in the laboratory with the treated rubber and its results. Despite the attempt to identify and explore optimum chemical treatment in the current study, further work is required to improve the mechanical behaviour from the test results as well as to optimise the chemical treatment in large size samples. This can either be achieved at the chemical treatment stage (through other quantities of chemical treatment systems), at the time of manufacturing the laboratory test samples and/or through field trials. More detailed testing is also required including the use of more established analysis techniques to study the migration of light fractions from bitumen to rubber.

2. Materials and methods

2.1. Materials

The crumb rubber utilised to carry out the treatment was 1–6 mm size aggregates from truck scrap tyres. The size range of the sample was obtained using a set of sieve by passing through a 6 mm sieve and retaining on 1 mm particle size sieve. It was supplied by J. Allcock & Sons based in Manchester, UK. The sample of waste rubber is shown in Fig. 1 and its physical properties are presented in Table 1. The bitumen was 100/150 penetration grade (pen) supplied by Nynas UK AB. The typical properties of the bitumen used in the study is shown in Table 2.

The chemicals used for the oxidation were potassium dichromate, ⩾99.5% supplied by Sigma Aldrich and potassium permanganate, 99% supplied by BDH Laboratory, England. The cross-linking agent used was polyethyleneimine supplied by Sigma Aldrich. Petroleum (petrol special) with aromatic basis (∼18%, bp. 180–220 °C) was supplied by Sigma Aldrich that was used to replicate the interaction effect of bitumen (because of their similar properties). This was to analyse the polyethyleneimine coating and its durability in petroleum.

2.2. Design of the chemical treatment

- The modification of waste rubber surface was a two stage process. In the first stage, *oxidation* of the crumb rubber was carried out. It was followed by the cross-linking of the rubber in the second stage. The most important factor in the current study was to optimise the chemical treatment and to identify the combination of the oxidation and cross-linking agents and their