Construction and Building Materials 172 (2018) 533–543

Contents lists available at ScienceDirect

Construction and Building Materials

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

Mechanical performance of steel fibre reinforced rubberised concrete for flexible concrete pavements

Abdulaziz Alsaif*, Lampros Koutas, Susan A. Bernal, Maurizio Guadagnini, Kypros Pilakoutas

Department of Civil and Structural Engineering, The University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, UK

HIGHLIGHTS

- Tough and flexible concrete is developed using recycled materials.
- Ductility is improved by adding steel fibres and further enhanced by adding rubber.
- The synergy between WTR and steel fibres improves the concrete flexural performance.
- Fresh & hardened properties of SFRRuC can be optimised for strength and toughness.

ARTICLE INFO

Article history:
Received 8 September 2017
Received in revised form 19 February 2018
Accepted 1 April 2018

Keywords:
Recycled fibres
Rubberised concrete
Steel fibre concrete
Rubberised steel fibre concrete
Hybrid reinforcement
Flexible concrete
Flexible pavements

ABSTRACT

This work aims to develop materials for flexible concrete pavements as an alternative to asphalt concrete or polymer-bound rubber surfaces and presents a study on steel fibre reinforced rubberised concrete (SFRRuC). The main objective of this study is to investigate the effect of steel fibres (manufactured and/or recycled fibres) on the fresh and mechanical properties of rubberised concrete (RuC) comprising waste tyre rubber (WTR). Free shrinkage is also examined. The main parameters investigated through ten different mixes are WTR and fibre contents. The results show that the addition of fibres in RuC mixes with WTR replacement substantially mitigates the loss in flexural strength due to the rubber content (from 50% to 9.6% loss, compared to conventional concrete). The use of fibres in RuC can also enable the development of sufficient flexural strength and enhance strain capacity and post-peak energy absorption behaviour, thus making SFRRuC an ideal alternative construction material for flexible pavements.

1. Introduction

Road pavements and slabs on grade are constructed either with flexible asphalt or rigid concrete. Flexible pavements can better accommodate local deformations, but lack the durability of concrete which is by nature much stiffer. A flexible concrete pavement could combine the advantages of both types of pavements, however, requires a radical change in how it is constructed. Rubberised concrete which can be design to have stiffness values similar to that of asphalt, can be used as an alternative construction material for flexible pavements. It is well known, however, that the use of rubber in substantial enough quantities can also adversely affect all of the other mechanical properties of Portland-based concrete. Furthermore, virgin rubber aggregates are significantly more expensive than natural aggregates. To address these issues, this study aims to use recycled materials derived from waste tyre rubber (WTR) not only to provide economically and structurally sound alternatives, but also to enable the development of a sustainable flexible concrete pavement solution.

1.1. Waste tyre materials

According to The European Tyre Recycling Association [1], approximately 1.5 billion tyres are produced worldwide each year and a quarter of this amount is arisen in EU countries. It is also estimated that for every tyre brought to the market, another tyre reaches its service life and becomes waste. The European Directive 1991/31/EC [2] introduced a set of strict regulations to prevent the disposal of waste tyres in landfills as a means of preventing environmental pollution and mitigating health and fire hazard [3–5]. As a result, in the EU any type of waste tyre disposal in the natural environment has been banned since 2006. The European Directive 2008/98/EC [6] has also established a disposal hierarchy leading to

---

* Corresponding author.
E-mail address: asaalsaif1@sheffield.ac.uk (A. Alsaif).

https://doi.org/10.1016/j.conbuildmat.2018.04.010
0950-0618/

a serious effort for effective waste tyre management, minimising energy consumption.

Typical car or truck tyres comprise 75–90% rubber, 5–15% high-strength corded steel wire and 5–20% polymer textile. WTR is currently used as fuel, in particular in cement kilns. It is also used in applications, such as synthetic turf fields, artificial reefs, sound proof panels, playground surfaces and protective lining systems for underground infrastructure [7,8]. While these applications make a positive contribution to recycling WTR, demand with respect to the volume of waste tyres is still small. Since cement-based materials constitute the largest portion of construction materials worldwide, recycling WTR in concrete is a positive way to respond to the environmental challenge and to the significant redundant volumes of waste materials.

1.2. Rubberised concrete

In the past two decades, several studies have investigated the addition of WTR in concrete, but only recently for structural applications [9–12]. Concretes containing rubber particles present high ductility and strain capacity, increased toughness and energy dissipation [11,13,14]. These properties, along with the material's high impact and skid resistance, sound absorption, thermal and electrical insulation [5,15–17] make rubberised concretes (RuC) a very attractive building material for non-structural applications.

Despite the good mechanical properties of rubber, production of RuC has several important drawbacks: (a) reduction in workability associated with the surface texture of the rubber particles [3,11,18,19], (b) increased air content as the rough and non-polar surface of rubber particles tend to repel water and increase the amount of entrapped air [20–22], and (c) reduction in the compressive strength (up to approximately 90% reduction with 100% replacement of natural aggregates), tensile strength and stiffness [11,23]. The reduction in mechanical properties is mainly attributed to the lower stiffness and higher Poisson's ratio of rubber (nearly 0.5) compared to the other materials in the mixture, and the weak bond between cement paste and rubber particles [21,24,25]. One of the potential alternatives to enhance the mechanical performance of RuC is the addition of fibres.

1.3. Steel fibre reinforced concrete using recycled fibres

The steel cord used as tyre reinforcement is a very high strength cord of fine wires (0.1–0.3 mm). The same cord is currently being used in limited volumes to reinforce concrete in high value security applications, such as vaults and safe rooms. At the same time when extracted from tyres, the cord is either discarded or at best re-melted. Commercially available steel fibre reinforcement for concrete comprises thin fibres with a diameter ranging from 0.3 to 1 mm and has a sizable market mainly in tunnel and slabs on grade applications. Hence, it is natural to consider tyre wire for concrete applications [26], as using recycled tyre steel fibres (RTSF) from waste tyres, instead of manufactured steel fibres (MSF), can reduce costs and positively contribute to sustainability by reducing the emissions of CO_2 generated from manufacturing steel fibres [27,28]. Recently, many studies have examined the use of recycled steel fibres in concrete [27,29–32]. By assessing mechanical properties, most of these studies confirm the ability of classified RTSF to reinforce concrete.

1.4. Steel fibre reinforced rubberised concrete

Despite the fact that there are many studies on RuC and SFRC, there are very few studies examining the effect of using steel fibres and rubber particles together in concrete, and most of these focus on cement-based mortars or self-compacted concrete (SCC) [33–37]. Turatsinze et al. [33] investigated the synergistic effect of MSF and rubber particles, in particular replacing sand in cement-mortars. They observed that the addition of steel fibres improved the flexural post-cracking behaviour, while the addition of rubber (up to 30% by volume of sand) significantly increased the deflection at peak load. Ganesan et al. [35] studied the influence of incorporating crumb rubber and MSF in SCC. Compared to conventional SCC, they reported a 35% increase in flexural strength when 15% of sand (by volume) was replaced with crumb rubber and 0.75% (by volume) fraction of steel fibres was added. Xie et al. [36] conducted an experimental study on the compressive and flexural behaviour of MSF reinforced recycled aggregate concrete with crumb rubber. They found that as the amount of rubber content was increased, the reduction in the compressive strength was smaller compared to other studies, and they attributed this behaviour to the inclusion of steel fibres. They also concluded that steel fibres played a significant role in enhancing the residual flexural strength, which was slightly affected by the increase in rubber content. Finally, Medina et al. [37] examined the mechanical properties of concrete incorporating crumb rubber and steel or plastic fibres coated with rubber. They observed that concrete with rubber and fibres presents better compressive and flexural behaviour as well as impact energy absorption than plain rubberised concrete.

To the best of the authors' knowledge only limited information is available on the mechanical behaviour of steel fibre reinforced rubberised concrete (SFRRuC) where both fine and coarse aggregates are replaced with rubber particles in significant volumes (exceeding 20% by volume of total aggregates) and further studies are needed to understand its performance where much larger rubber volumes are used. Large volumes of rubber are necessary to achieve more flexible concrete pavements. In addition, the behaviour of SFRRuC in which RTSF are used alone or in a blend with MSF, has not been studied yet.

This study investigates the fresh properties as well as the compressive and flexural behaviour of several SFRRuC mixes with the aim of developing optimised mixes suitable for pavement applications. Coarse and fine aggregates are partially replaced by different sizes and percentages of tyre rubber particles and various dosages and blends of steel fibres, MSF and/or RTSF, are used as fibre reinforcement. Details of the experimental programme and the main experimental results are presented and discussed in the following sections. This study contributes to the objectives of the EU-funded collaborative project Anagennisi (http://www.anagennisi.org/) that aims to develop innovative solutions to reuse all waste tyre components.

2. Experimental programme

2.1. Parameters under investigation

The parameters assessed in this study were: (i) the rubber content used as partial replacement of both fine and coarse aggregates (0%, 20%, 40% or 60% replacement by volume), and (ii) steel fibre content (0 or 20 kg/m^3 MSF + 20 kg/m^3 RTSF, or 40 kg/m^3 RTSF). A total of 10 different mixes were prepared. For each mix, three cubes (150 mm-size), three cylinders (100 mm-diameter and 200 mm-length), and three prisms (100 × 100 mm-cross section and 500 mm-length) were cast. The cubes and cylinders were used to obtain the uniaxial compressive strength and the compressive stress–strain curve, respectively, whereas the prisms were cured in different conditions to evaluate free shrinkage strain (autogenous and drying) and then subjected to three-point bending. Table 1 summarises the different mix characteristics and the ID assigned to the mixes. The mix ID follows the format NX, where N denotes the amount of rubber content used as partial replace-