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Durability of steel fibre reinforced rubberised concrete exposed to chlorides

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HIGHLIGHTS

- SFRRuC can be used as an alternative flexible pavement.
- SFRRuC resist chloride permeability.
- No steel fibre corrosion is found after 300 days of wet-dry chloride exposure.
- Water absorption of SFRRuC falls within the highly durable concrete mixes range.

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ABSTRACT

This study assesses the durability and transport properties of low water/binder ratio (0.35) steel fibre reinforced rubberised concrete (SFRRuC) mixes, which are proposed to be used as flexible concrete pavements. Waste tyre rubber is incorporated in concrete as fine and coarse aggregate replacement and blends of manufactured steel fibres and recycled tyre steel fibres are used as internal reinforcement. The fresh, mechanical and transport properties of plain concrete are compared with those of SFRRuC mixes having different substitutions of rubber aggregates (0, 30 and 60% by volume). The chloride corrosion effects due to exposure to a simulated accelerated marine environment (intermittent wet-dry cycles in 3% NaCl solution) is also evaluated. The results show that, although water permeability (e.g. volume of permeable voids and sorptivity) and chloride ingress increase with rubber content, this increase is minor and water and chlorides permeability are generally within the range of highly durable concrete mixes. No visual signs of deterioration or cracking (except superficial rust) were observed on the surface of the concrete specimens subjected to 150 or 300 days of accelerated chloride corrosion exposure and a slight increase in the mechanical properties is observed. This study shows that the examined low water/binder SFRRuC mixes promote good durability characteristics, making these composite materials suitable for flexible concrete pavement applications.

1. Introduction

Several factors are considered when designing road pavements including traffic loading, sub-grade status, environmental conditions, as well as cost and availability of construction materials. Two different systems of pavements are conventionally used in roads construction: flexible asphalt or rigid concrete. A flexible pavement typically consists of a series of layers and its design is based on distributing the load through the component layers. On the other hand, a rigid pavement typically consists of one Portland cement concrete structural layer and its design is based on the flexural resistance of this layer. Flexible asphalt pavements have low stiffness and as such they can better accommodate deformations arising from temperature changes, loads and soil movements, however, lack the durability resistance of rigid concrete pavements which are longer lasting [1]. It is therefore desirable to develop a pavement system with comparable flexibility to asphalt pavement, and ability to withstand higher stresses as well as environmental attack during its service life. One attractive alternative proposed by the authors is concrete pavements that include high amounts of recycled rubber particles (chips and/or crumbs), as a partial replacement of natural aggregates, and recycled steel fibre reinforcement. These composite concretes, referred to as steel fibre

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reinforced rubberised concretes (SFRRuC), can be designed to have high flexibility similar to asphalt and flexural strengths similar to steel fibre reinforced concrete (SFRC) [1].

Over the past two decades, research interest in the potential use of waste tyre rubber (WTR) as partial replacement of natural aggregates in the production of concretes (rubberised concretes – RuC) has steadily grown [2–6]. RuC present reduced workability and increased air content, compared to conventional concretes, as a result of the rough surface texture of the rubber particles [4,7–9]. Though RuC can show higher ductility and increased toughness compared to conventional concrete [8–10], this is at the expense of loss in strength and stiffness [11,12]. Different strategies to improve the mechanical performance of RuC have been investigated in recent years, including the addition of supplementary cementitious materials to the binder mix to reduce the porosity and aid early age strength development. For example, Raffoul et al. [9] observed a 40% enhancement in the compressive strength of RuC when 20 wt% of cement was replaced with equal amount of silica fume and fly ash. This enhancement was attributed to the better particle packing and cohesion of the concrete mix as a result of the reactivity of these materials and the consequent pozzolanic reaction.

The addition of fibres to RuC can enhance the mechanical performance of these composite concretes. Xie et al. [13] reported that the inclusion of manufactured steel fibres (MSF) in RuC, mitigated the reduction in compressive strength while increasing residual flexural strength. Similar outcomes were reported in other studies by the authors [1,2] where SFRRuC presented better mechanical properties than plain RuC. Although the fresh and mechanical properties of RuC and SFRRuC have been studied by several researchers, there is still a dearth of data in this field, especially when rubber aggregates are incorporated in the large volumes (exceeding 20% replacement by volume of total natural aggregates). It should be noted that, large volumes of rubber aggregates replacements in concrete are necessary to attain flexibility in concrete pavements.

Few studies examined the durability and transport properties of RuC, with notable discrepancies being reported on the effect of rubber particles on long-term performance. Water permeability and water absorption by immersion generally increase with rubber content [14–16]. This has been attributed to the additional water required in RuC mixes to maintain workability, and the high void volumes between rubber particles and cement paste due to the hydrophobicity of rubber. Conversely, several researchers have observed a reduction in water absorption of RuC (up to 12.5% rubber for fine aggregates) using the method of immersion and related this behaviour to the impervious nature of rubber particles. Benazzouk et al. [17] reports that the addition of rubber crumbs of up to 40% volume in cement pastes reduced sorptivity, hydraulic diffusivity and air permeability. Similar observations are reported by Segre and Joekes [18] who also attributed this behaviour to the hydrophobic nature of rubber. The transport properties of these composite concretes are strongly dependent on the distinctive features of the starting concrete matrix, whose performance can significantly vary as a function of mix design, age and curing conditions, among other factors, which explains the variability in results obtained from different investigations.

In a recent study, the authors [1] studied the mechanical properties of SFRRuC mixes in which fine and coarse aggregates were partially replaced with rubber (0%, 20%, 40% or 60% replacement by volume), and different types of steel fibres (MSF and/or recycled tyre steel fibres – RTSF) added in volumes of up to 40 kg/m^3. In addition to the increased toughness and flexibility attained, it was observed that all the examined SFRRuC mixes were able to achieve flexural strengths that meet the flexural strength limits prescribed in pavement design EN 13877-1 [19]. Concrete pavement slabs, however, are susceptible to several deteriorative processes that can be caused by the ingress of aggressive substances into concrete, such as corrosion due to attack by chlorides or carbonation. The rate of transport of aggressive agents is related to a large degree to the concrete's degree of saturation and air permeability [17]. Aggressive substances such as chlorides can also penetrate into concrete due to diffusion and capillary action.

The chloride permeability in RuC remains largely unknown and studies examining this [20,21] reveal increased chloride permeability with rubber content, which can be significantly reduced with the addition of fly ash and/or silicate fume. This is consistent with the reduced water absorption and permeability achieved in concretes with these additions [15,20]. To date, there are very few studies on the transport and durability properties of RuC with large volumes of rubber replacement [7,22,23], while the transport and durability properties of SFRRuC has not been studied yet. Furthermore, there is limited understanding on the mechanism governing chloride-induced corrosion of steel fibres in RuC and its potential effect on long-term performance. However, there is a good consensus that the main factors controlling durability of SFRC, when exposed to chlorides, include: (i) the age and the exposure conditions, (ii) the steel fibre type and size, (iii) the concrete matrix quality and (iv) the presence of cracks [24]. Consequently, it is important to understand the transport and durability properties of SFRRuC before using it in flexible concrete pavements.

In this study, the fresh state, mechanical strength, and transport properties of SFRC, and SFRRuC are investigated and compared. The fresh properties assessed include workability, air content and fresh density. The mechanical performance is examined in terms of compressive strength and flexural behaviour including flexural strength, elastic modulus and residual flexural strength. The transport properties examined are volume of permeable voids, gas permeability, sorptivity and chloride penetrability (chloride ion penetration depth and diffusion). The chloride corrosion effects due to exposure to a simulated accelerated marine environment (intermittent wet-dry cycles in 3% NaCl solution) are also evaluated.

2. Experimental programme

2.1. Materials and mix designs

2.1.1. Materials

A Portland limestone cement CEM II-52.5N, in compliance with EN 197-1 [25] and containing 80–94% Portland cement clinker, 10–15% limestone and 0–5% minor additional constituents, was adopted as the primary binder in this study. Silica fume (SF) and fuel ash (FA) were also used (10 wt% for each) to improve particle packing (or filling) in the mixture [9] as well as to reduce permeability and enhance concrete strength. Two types of high range water reducer HRWR admixtures, plasticiser and superplasticiser, were also added to achieve the desired workability. A water/binder (Portland cements + silica fume + fly ash) ratio of 0.35 was used in all mixes.

The coarse aggregates were river gravel with particle sizes of 5/10 mm and 10/20 mm, specific gravity (SG) of 2.65 and water absorption (A) of 1.2%. The fine aggregates were river sand with particles sizes of 0/5 mm, SG of 2.64 and A of 0.5%.

The rubber aggregates were recovered by the mechanical shredding of vehicular tyres. Rubber particles were sourced in the following size ranges: 0/0.5 mm, 0.5/2 mm and 2/6 mm, 5/10 mm, and 10/20 mm. A relative density of 0.8 (measured using a representative volume of rubber) was used for the rubber to determine the appropriate replacement by volume. Fig. 1 shows the particles