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Fatigue performance of waste rubber concrete for rigid road pavements

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HIGHLIGHTS

- Estimation of fatigue life of rubberized concrete for rigid pavements was assessed.
- Optimum combination of size and percentage of rubber particles was explored.
- A novel test was specifically designed to simulate traffic load conditions.
- Optimizing size and proportion of added rubber enhances durability of concrete pavements.

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ABSTRACT

The handling and storage of end-of-life tyres is an environmental problem and constitutes a considerable worldwide challenge. This paper investigates the suitability of using discarded waste tyre rubber particles in concrete rigid road pavements. The objective is to optimize size and proportion of rubber particle to improve the material performance. A tests program was carried out to know the effect of rubber size and rubber content on mechanical properties of concrete pavements. Mixtures with rubber particles of variable sizes (1–4, 10 and 16 mm) added in different proportions (10, 20 and 30%) are considered. A novel test to evaluate deformation (in terms of transversal micro-cracks) suffered by the material under cyclical efforts similar to traffic loads is proposed. The results show that there exists an optimal combination of size and proportion of rubber particles that improves the performance of the material under cyclic load stresses, which makes the material suitable for the construction of rigid concrete pavements.
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1. Introduction and objectives

There is an increasing concern over the high levels of waste generation per capita, especially waste elements that are impossible to split into original components, such as rubber waste derived from end-of-life tyres. According to the predictions made by the LMC Automotive, by 2024 the vehicle fleet will have grown by >25% worldwide and is estimated that around 355 million tyres are produced in the EU per annum [1,2]. Contrary to other products such as paper or glass, the use of recycled material in the manufacture of new tyres is impractical, among other aspects due to strict safety requirements [3], therefore, the increasing demand of new tyres brings about more raw materials consumption. In this context, Europe is currently facing the challenge of reducing the consumption of raw materials, particularly those that are import-dependent, such as natural rubber. In 2008, the European Commission approved The Raw Materials Initiative, establishing a strategy to address the problem of access to raw materials, based on a fair and sustainable supply of "secondary raw materials" obtained through recycling [4].

Waste tyre rubber has been characterised as a toxic and hazardous waste [5]. Recovery and disposition of end-of-life tyres is recognized as "black pollution" [6], as this waste has a strong environmental, economic and social impact. A large part of discarded tyres ends up stockpiled in waste disposal sites (usually unsupervised) without having been subjected to any specific treatment prior to storage. The growing number of these waste disposal sites poses phytosanitary risk, increasing likelihood of fires and segregation of the space they occupy in relation to their environment. The handling and storage of end-of-life tyres is already an environmental problem with public health and aesthetic implications in developed countries, and it is becoming problematic in developing countries. The increase in per capita income favours the expansion of automobile for personal use as well as public investments in road systems, which encourages the purchase of new vehicles and consequently the increasing of discarded tyres [7].

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The handling of waste tyres constitutes a considerable challenge, due to the difficulty to turn the material into a reusable raw material. In an attempt to reduce the magnitude of this issue, the scientific and technological community is trying to develop alternatives for worldwide reduction and recycling of this product. Waste tyres can be utilized in several construction materials, such as asphalt, culverts, bricks, paving blocks and acoustic panels [8]. Among these recycling options, the industrial use in concrete manufacturing offers great potential in large-scale consumption of these waste materials. The production of concrete with rubber as a substitute of aggregates is an emerging field for the reuse of discarded tyres [9,10], being applicable not just in plain concrete, but also in roller-compacted concrete, self-compacting concrete and high strength concrete. This solution is environmentally beneficial and allows reducing the amount of material stored in waste disposal sites.

Road pavements are constantly subjected to high level of loads acting in a cyclic manner. The derived damage needs unexpansive and speedy repairing, in order to avoid traffic interruptions. Only in Spain, for instance, maintenance of road surfaces takes up to 80% of financial investment in road management. For this reason, most intervention is limited to prompt repairs. This methodology, however, has the following flaws: (i) a punctual action does not eliminate the root of the problem; and (ii) additional material is used for repairing works. The use of high-performance materials, extends the useful life of pavements, reducing maintenance and repair costs, along with the consumption of additional materials and the inconvenience caused to the users. Currently, there is a growing interest in the use of rigid concrete for roads, due to enhanced durability, with the aim to reduce the increasing cost and strong environmental impact that products deriving from oil causes, which are usually used in asphalt pavements. However, the environmental impact of concrete should not be ignored, and new material formulations must be proposed to increase the useful life of road pavements and reduce the need to use materials in maintenance.

The inclusion of rubber from discarded tyres in concrete pavements is an interesting alternative that provides a novel use for this material once the tyre has finished its useful life. This alternative allows reducing the amount of waste collected in landfills, as well as diminishes the volume of raw materials needed for new roads (and consequently remarkably reduces the environmental impact associated with mining such resources). Finally, certain critical properties of concrete pavements would also be improved, such as the durability for cyclic efforts and the level of noise produced, increasing the safety and comfort on the roads. Therefore, reusing this material in concrete road pavements clearly provides environmental and social benefits.

The objective of this paper is to evaluate the fatigue performance of concrete mixed with discarded waste tyre particles. For that purpose, a test was specifically designed to simulate the load conditions to which a rigid pavement would be subjected due to traffic loads. Measurements of deformation of the material over the course of the test are also intended. An experimental program was conducted using rubberized concrete with different content of rubber of several sizes each time. Mechanical properties and fatigue performance were evaluated and compared with plain concrete. As an innovative approach, the methodology proposed in the present study (a) considers one rubber particle size by each mix in different proportions, and (b) evaluates deformation (in terms of transversal micro-cracks) suffered by the material under cyclic loads during the test period. Therefore, this research aims to explore the optimum combination of size and percentage of the rubber to be added to the material for improving resistance and deformation under cyclic loads.

2. Literature review

2.1. Effect of rubber on the properties of concrete

The addition of rubber to the concrete mixture implies the introduction of a flexible material in a rigid compound altering its performance and properties. Thus, the density of the material gets reduced because rubber is less dense than traditional aggregates [11], along with variations of the water absorption coefficient [12] and permeability [13]. The particle size of waste tyre rubber clearly affects load transfer capabilities [14], and is well known that the bond between rubber particles and cement paste is weaker than in traditional rigid aggregates [15]. Consequently, the optimization of the rubber particle sizes allows improving the interaction between the components of the mixture. Depending on nominal size, rubber particles are classified as ash, granular or fibbers (see Table 1) [11,16–19].

The origin and form of the rubber is of vital importance, as affects the workability of the mixture [18]. Large quantities of rubber reduce significantly the workability of the mixture; it is estimated that a rubber content of 40–45% of the total volume of aggregates produces a reduction of the flow of concrete and makes difficult to handle it manually [20]. Kotresh et al. reported a worsening of workability with an increase in slump test value of 17% for a 10% chipped tyre rubber [21]. Gupta et al. managed to keep the workability of the material by varying the quantity super plasticizer around 3% for mixes with 0 to 25% of partial replacement of fine aggregate by rubber fibbers [11]. Although this reduction of workability is widely accepted [22], these authors exclusively analysed one size of rubber particles, leaving room for studying the possibility that smaller sized particles might produce loss of workability.

Generally speaking, the concrete resistance to compression is reduced with either sand or coarse aggregate substitution or replacement. Compressive strength reduction around 46–48% has been reported for a 20% replacement of fine aggregates [23]. Similar results were reported for a 20% replacement of coarse aggregate [19]. A maximum of 92% of compressive strength was obtained by a 100% of rubber replacing fine aggregates (0–5 mm size) [20]. Recently, Rezaifar et al. demonstrated that this negative effect is mitigated when metakaolin is incorporated in the mix [8]. After an optimization analysis, the authors stated that the combination of 3.3% volume replacement of sand by crumb rubber and 19.5% volume of cement replacement by metakaolin maximized the compressive strength and minimized water absorption. The addition of nanosilica also mitigates this compressive strength loss, moreover an increase of the elastic modulus of rubber concrete was observed [24].

Resistance to bending tension and tensile strength are also reduced when adding rubber to the concrete, mainly due to significant differences of the elastic modulus of both materials [25]. Likewise, there is a consensus regarding improvement of impact

Table 1
Classification of the rubber particles used in previous studies according to size.

Name	Size	Ref.
Ash	0.15 –1.9 mm	[16]
Granular		
Fine aggregate	<4.75 mm; >75 μm	[17]
Crumb rubber	4.75 mm	[18]
Coarse aggregate	>4.75 mm	[19]
Chip	<12 mm	[11]
Fibers	2–5 mm in width; up to 20 mm in length	[11]

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