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Damage propagation rate and mechanical properties of recycled steel fiber-reinforced and cement-bound granular materials used in pavement structure

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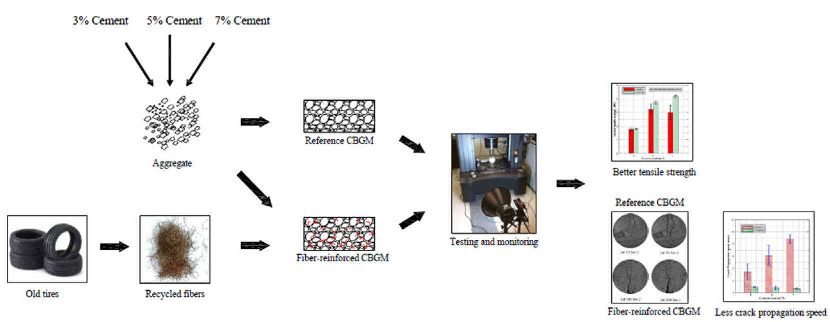
HIGHLIGHTS

- Improvement in tensile strength after recycled fiber and cement inclusion.
- Toughness enhancement comes from the less crack propagation speed.
- Increase of cement content decelerates the crack speed for fibrous mixtures.
- Crack diffusion rate decreased due to reinforcement and higher cement contents.
- The benefits gained from fiber inclusion increases with higher cement contents.

GRAPHICAL ABSTRACT



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ABSTRACT

Cement-bound granular mixtures (CBGMs) represent an attractive option to increase load-carrying capacity and sustainability in highway construction. However, reflection cracking of overlying pavement layers due to the low tensile strength of CBGMs represents an important obstacle limiting their use. This study is undertaken to investigate how incorporation, in CBGMs, of recycled steel fibers extracted from old tires, at different cement levels may affect their tensile properties related to pavement design. A combination of three levels of cement (3%, 5% and 7% by wt. of aggregate and fiber) and two reinforcement contents (0% and 0.5 by volume of aggregate) was investigated. To comprehensively quantify the benefits of fibers in the presence of variable cement contents, time-dependent fracture and damage propagation were examined quantitatively utilizing a combination of macro-surface cracks, fractal analysis and both image monitoring and processing techniques. The results indicated better tensile strength and toughness after cement and fiber inclusion. Furthermore, increasing the amount of cement accelerates the crack propagation and damage dispersion rate while these two parameters reduced significantly in the case of fiber-reinforced cemented aggregate. All benefits gained from fiber usage are more evident at higher cement contents.

1. Background

Cement stabilized aggregate mixture is cementitious material that consists of aggregate, cement and a small amount of water. Over the years, researchers have attempted to use other stabilizers

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such as lime [1], flyash [2], kiln dust [3] and geopolymers [4]. To save natural resources and to encourage sustainable solutions, many investigations have been conducted to replace the natural aggregate by recycled aggregate such as recycled concrete aggregate RCA [5] and recycled asphalt pavement RAP [6,7] or including waste aggregate such as a mix of construction and demolition waste CDW [8] and glass materials [9].

Cement stabilization of granular materials, intended to be used as a main structural layer within semi-rigid pavements, has been proved as an effective technique giving better protection of weak subgrades and enhanced support for the surface hot mix asphalt layer. However, the inherent crack susceptibility of this layer, either due to shrinkage or due to low tensile capacity, might forms an obstacle that reduces the benefits of the technique. The crack networks that develop normally affect these stabilized layers detrimentally since they reduce the structural integrity, contributing negatively to load-carrying capacity, and most importantly increase the possibility of reflection cracking, especially in the case of wide cracks.

Many attempts have been made to overcome the disadvantages that accompany application of cement stabilization in pavement construction. Shahid and Thom [10], Thom et al. [11], and Coni and Pani [12], for example, tried to use industrial steel fibers as a reinforcement and investigated how such reinforcement might affect the mechanical properties of cement-stabilized aggregate mixtures. Their results indicated the better mechanical behavior of the composite. Different types of fiber have also been used in many applications to improve the properties of different types of chemically stabilized soils [13–16]. Coni and Pani [12] claimed that the initial cost of this industrial fiber might make it an uneconomic option while Sobhan and Mashnad [17] and Sobhan and Mashnad [18] justified their design in the light of other benefits such as longer fatigue life and reduced layer thickness. Nevertheless, they later attempted to use the waste fibers extracted from old milk containers to reduce the initial cost of the fibers and hence reduce the pavement construction cost while ensuring better performance and a sustainable pavement structure. In their study, Zhang et al. [19] used polypropylene fibers as a low price reinforcement in CBGMs. Improvement in fracture properties was the main outcome of their investigation. More recently, Farhan et al. [20] and Farhan et al. [21] used rubber particles from recycled vehicle tires as replacement for fine aggregate to modify the aggregate mixture and hence ensure better mechanical and cracking behavior. These rubber particles, as their results indicated, affect many of the mechanical properties detrimentally but achieve better cracking characteristics.

In order to improve mechanical properties while ensuring reduced cost and maintaining sustainable pavement structure, an attempt is made in this paper to use recycled steel fibers from old tires as a reinforcement. Despite the recent use of this recycled reinforcement in different types of concrete as reported in many investigations [22–24], the use of recycled steel fibers has never been attempted in cement-stabilized aggregate at relatively low cement contents.

Investigation of damage propagation and cracking patterns is of the utmost importance since it will help in the understanding of damage and hence failure mechanisms which will eventually lead to more optimized mixtures [25]. For concrete mixtures used in different civil engineering structures, many studies have been conducted to examine the crack propagation speed in both plain and fiber-reinforced concretes. Mindess [26] conducted a study to show how fiber inclusion in normal concrete mixtures affects the crack propagation speed. He reported a decline in crack speed after steel fiber inclusion. Pyo et al. [27] noted that the number of studies to characterize crack propagation in fiber-reinforced concrete is very limited compared to those performed for plain concrete and, accordingly, they studied the effect of fiber and loading rate on crack propagation speed in ultra-high strength concrete. Their findings indicated a drop in the crack propagation speed due to fiber reinforcement.

To the best knowledge of the authors, all of the above-mentioned studies to investigate the impact of fibers (either industrial or recycled) have focused on the mechanical properties only and no study has so far been conducted to investigate crack propagation in either plain or fiber-reinforced cement-stabilized mixtures. Furthermore, the role that cement content might play in this process is still unclear. Therefore, this study has been undertaken to investigate how fiber inclusion at various cementation levels might affect the mechanical properties and to understand the effect of fiber inclusion on the crack propagation process in cemented aggregate, as a time-dependent phenomenon.

2. Experimental methodology

2.1. Materials

A limestone aggregate from Tunstead Quarry, Derbyshire, UK was used in this study. The gradation is shown in Fig. 1 together with specification limits.

To reduce the cost and increase the sustainability of highway pavement construction, recycled steel fibers (Fig. 2) were incorporated to reinforced cement-stabilized aggregate mixtures. These were extracted from old vehicle tires by a shredding process. The maximum fiber volumetric content attempted in cement-bound granular materials (CBGMs) is 1% as documented in previous literature [10,11]. Trial investigations at the start of the current experimental program showed there was difficulty in achieving uniform fiber dispersion due to fibers balling at 1% volumetric content. To ensure uniformity of fiber dispersion, a 0.5% volumetric content was selected.

Portland cement (CEM I 52.5 N) was used for the purpose of stabilization and binding the mixture components. To examine the effect of stabilizer content on the performance and effectiveness of fibers in CBGMs, three different stabilization levels, 3%, 5% and 7% by dry weight of aggregate and fibers were used. These cement

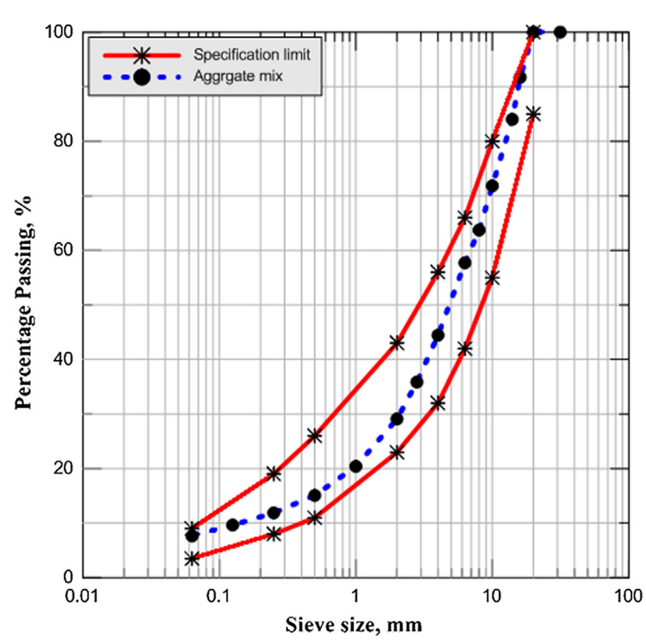

Fig. 1. Gradation of aggregate.