Construction and Building Materials 78 (2015) 439–449

Contents lists available at ScienceDirect

Construction and Building Materials

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

Dovetailed and hybrid synthetic fibre concrete – Impact, toughness and strength performance

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HIGHLIGHTS

- Dove tailed fibres provide load transfer at high strain rates.
- Dovetailed and polyethylene fibres transfer strain hardening post crack forces.
- Energy absorption in enhanced with the use of synthetic fibres.
- Post impact structural integrity is maintained with fibres in concrete.

ARTICLE INFO

Article history:
Received 9 September 2014
Received in revised form 9 December 2014
Accepted 2 January 2015
Available online 20 January 2015

Keywords:
Impact
Flexural toughness
Hybrid synthetic fibres
Ballistic

ABSTRACT

Concrete is a widely used material within the civil engineering environment, having many varied applications that utilise its inherent qualities. When concrete is subject to rapid or impact loading it can suffer failure as it is inherently weak in tension. The inclusion of fibres may go some way to mitigate this weakness. This paper investigates a new synthetic dove tailed (DT) cross section fibre with regard to energy absorption and builds upon previous pull out testing by the authors.

The test examines polypropylene DT fibres and hybrid blends of DT and other structural synthetic fibres to evaluate the best performing hybrid mix. The parameters of the test are: compressive strength, flexural strength, energy absorption (toughness) measured with load and deflection and time dependant absorbed energy using a drop hammer impact test and high velocity ballistic rifle fire.

The findings showed a 50%/50% mix of DT and Type A polyethylene fibre of a smaller diameter outperformed the other DT and hybrid fibres tested.

The single size prototype DT fibre is in its development stage and the results suggest a smaller diameter fibre may be more effective at coping with post crack forces. This specification change may prove beneficial with regard to enhanced energy absorption and will have many practical applications ranging from blast and projectile protection, motorway barriers, pre cast concrete impact damage, airport runway, rail system infrastructure and earthquake design.

1. Introduction

The purpose of the test program was to compare dove tailed (DT) fibres in concrete with hybrid blends of fibres, against a plain concrete control sample when subject to flexural, impact and ballistic testing. The motivation for the work is to develop safer blast resistant materials. The reason for using hybrid fibre mixes was informed by Hsiem et al. [1], as they suggested, polypropylene hybrid fibre reinforced concrete is better than the properties of a single fibre reinforced concrete and the two forms of fibres work in a complimentary manner. The decision to use a hybrid mix was also supported by two of the authors earlier work [2] in which the pull out test findings showed that large degrees of toughness was available when using DT fibre technology. However this earlier work also demonstrated that the DT fibres transferred less bond stress at the point of the initial pull out prior to the DT flute feature of the fibre taking effect. The tensile loading of the DT fibre caused the longitudinal flutes to close around the embedded concrete, this provided additional grip when the cement/fibre bond had been broken. The fibre types A (polyethylene) and B (polypropylene) [2] provided a higher pull out value at the point of initial fibre movement and they failed by breaking, whereas the DT fibres failed by pull out. Bentur and Mindness [3] have suggested that enhanced performance of hybrid mixes in terms of engineering

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http://dx.doi.org/10.1016/j.conbuildmat.2015.01.003
0950-0618/

performance may utilise the best qualities of each fibre type and this test investigates these qualities with regard to engineering properties. Hsiem et al. [1] suggest the use of polypropylene fibres will increase the ductility of concrete and this parameter may be of use when absorbing impact energy.

Concrete with a high degree of toughness is desirable in many areas of construction and infrastructure provision. Motorway barriers, blast and projectile resistance barriers, industrial floors, airport runways and earthquake resistant design all achieve enhanced performance characteristics with high levels of toughness and energy absorption.

1.1. Fibre use in concrete slabs

The post crack performance of reinforced concrete can be improved with the use of steel rebar, steel fabric or fibres. Destrée [6] reports that it is now possible in some concreting applications, to replace traditionally used reinforcement, with fibres alone. The individual performance of synthetic and steel fibres vary considerably due to steel having an elastic modulus in region of 205,000 N/mm^2 whereas polypropylene has an elastic modulus of around 3500 N/mm^2 and polyethylene 5000 N/mm^2. The individual load transfer capacity of steel and synthetic fibres varies considerably due to different modulus of elasticity, section profile and their ability to bond to the concrete matrix. When all of these parameters are considered it is very difficult to equate equal performance using very different materials with different shapes, aspect ratios, bond strength and tensile capacity. However it can be achieved using varying fibre dosages [4,5].

It is generally accepted the strength of the concrete has little effect on the failure load for the fibres, as it is the bond between the concrete and the fibre that breaks first [7]. The final post crack load will be influenced by fibre direction, total number of fibres at the cracked cross section, fibre type and concrete type. Parviz and Lee [8] concluded that, only 65% of the fibres should be considered for structural analysis, and from previous research [9] it should be considered that this figure may be slightly too high and caution should be exercised when establishing performance parameters. The energy absorption performance of fibre reinforced concrete slabs forms part of the investigative scope of this research and Section 1.2 highlights the factors to be considered.

1.2. Impact/blast/projectile resilience

Typically, when an explosion occurs adjacent to a steel (rebar) reinforced concrete wall, a proportion of the energy will travel through the wall as a 'compressive stress wave'. As the wave meets the back face of the wall it partly rebounds, with some energy travelling back through the wall, and some travelling into the air. The rebound of the 'compressive stress wave' within the concrete can cause a tension rebound. As the concrete fails in tension, back face spalling can occur, ejecting concrete fragments at high speed [10]. The reason for the ejection of concrete under blast load is due to the fact that concrete is unreinforced between the steel reinforcement bars and the spacing of reinforcement is crucial to the performance of the fragmentation. Fibres of any type will assist in providing crack control under load. Synthetic fibres elastic properties may be of benefit under these loading conditions. Secondary injuries can be caused by energised fragments of concrete. Concrete spalling is where fragments of concrete are forced from the opposite side of a concrete building element, which has been subjected to an impact or blast load [11]. When a concrete element is subjected to a blast load it deflects until the point where the strain energy of the element is equal to balance the energy of the blast load and the concrete element either comes to rest or it fragments and cracks [12]. It is vital to improve energy absorption of concrete and reduce fracture/cracking and spalling so that concrete components of a building do not fragment. The blast can displace and energise building components which then become projectiles with the potential to cause penetrating injuries. Elsayed and Atkins [13] note that this type of injury appears to be the most common. "Penetrating injuries due to an explosion are termed secondary injuries... they are often the primary [main] cause of the injuries." This trend was apparent for the Madrid metro bombings, Gutierrez de Ceballos et al. [14], state that shrapnel wounds accounted for 36% of all injuries. There is a requirement to reduce concrete spalling and cracking, so that the material does not fragment creating lethal projectiles and high dosage synthetic fibres may improve the performance of concrete in these situations. The reason for this was outlined by Hibbert and Hannant [15] who comment that, "Polypropylene fibres increased the energy absorbed in failure to at least ten times that of plain concrete" and Betterman et al. [16] state, short, small diameter fibres are more efficient in increasing the first peak stress. This may be due to the fact that opening and propagating of numerous micro cracks are primarily responsible for the magnitude of the first peak stress. A large number of short, small diameter fibres may effectively bridge these micro cracks.

1.3. Summary of current research

The literature has shown that fibre inclusion in concrete slabs may offer significant enhancement to the flexural toughness and energy absorption characteristics of concrete. Particular consideration has promoted the adoption of hybrid fibre mixes which are shown to outperform single fibre type mixes. The following investigation pursues these ideas through a detailed test programme.

2. Materials

The rationale for the mix design was to represent a commonly used mix rather than a very specialised bespoke mix and to include fibres into the mix.

2.1. Concrete mix design

The concrete mix design used, is in accordance with BS EN 14845-1:2007, [17], (reference concretes for fibre testing) where the maximum cement content was applied to the design mix. It was chosen to ensure adequate cement paste was available to coat the fibres. The 28 day C50 plain concrete design mix was composed of 400 kg CEM 1 cement (42.5 N), 40 kg silica fume, 731 kg coarse sand (<4 mm), and 1057 kg of 10–16 mm marine gravel sandstone aggregate with a 0.5 water/cement ratio. The cement type is defined within BS EN 197 [18] and the aggregates are UK sourced. The quality of the mixing water for production of concrete can influence the setting time, the strength development of concrete and the protection of reinforcement against corrosion. Potable water, described as water which is fit for human consumption is suitable to use according to BS EN 1008: 2002 [19], was used in the batch production.

2.2. Fibre types

BS-EN14889-2 [20] covers the classification of synthetic fibres and their manufacture, and divides polymer fibres into two main classes according to their physical form, these are Class 1a (<0.3 mm) monofilament and Class 2 (>0.3 mm) fibres, the latter of which are generally used when an increase in residual post crack strength is required. The tensile strength of macro synthetic fibres varies according to the manufacturer; the method of manufacture, and the polymer types used in the

Table 1
Fibre types.

Fibre type	Dimensions (mm)	Material	Aspect ratio
Dove tailed 20	2×60	Polypropylene	30
Type A	50×0.941	Polyethylene	53.1
Type B	50×1.183	Polypropylene	42.3