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The addition of synthetic fibres to concrete to improve impact/ballistic toughness

Alan Richardson *, Kathryn Coventry, Thomas Lamb, David Mackenzie

Northumbria University, Newcastle upon Tyne NE1 8SA, UK

HIGHLIGHTS

- This paper examines the impact performance of fibre concrete compared to plain.
- Type 2 fibre concrete has superior fragment containment.
- Finite Element Analysis was reliable to predict the damage of the concrete slabs.

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ABSTRACT

Concrete is relatively weak in tension and may require some form of reinforcement to cope with tensile forces. Steel reinforcing bar is often used to cater for tensile and compressive forces. However, current research shows that the use of steel reinforcing bar does not afford concrete protection against impact. Alternatively it has been shown that where fibres are added to concrete mixes protection is afforded through increased energy absorption. It would appear that the dispersion of fibres throughout a concrete mix affords a degree of toughness between the reinforcement bar spacing.

This research investigates the use of Type 1 micro synthetic fibres, Type 2 macro synthetic fibres and steel fibres used as post crack reinforcement in concrete samples when subject to a variety of stress induced states and compares the performance of these fibre mixes to that of a plain concrete mix. The test programme adopted, subjected cube specimens to compressive strength tests, beam samples to both three point flexural bending and single point impact loading, and concrete slab sections to shot gun fire. The parameters investigated under test were: compressive strength, flexural strength, load deflection analysis, energy absorption and impact performance/resistance. Modelling the impact of shot fire on the test specimens was carried out using Finite Element Analysis, to inform slab design. The results of this investigation are of particular significance to the resilience of concrete structures under terrorist attack.

The results show that the adoption of Type 2 macro synthetic fibres as concrete post crack reinforcement provide the greatest toughness when compared with the other fibre types and offer the greatest protection from spalling of the back face of the concrete slab, being the main consideration with regard to the performance of the slab on testing with shotgun fire. Damage containment after ballistic testing was also noted where Type 2 fibres were used. The Finite Element Analysis models were successful at predicting the damage recorded to the concrete slabs, when subject to the shotgun fire performance test.

1. Introduction

Combatting terrorism remains significant to the agendas of many governments of the developed world. However, fibres may be used to improve the impact resistance of concrete [3]. Coughlin et al. [3], concluded that fibre reinforced concrete performed better than plain reinforced concrete when subjected to external forces. Performance enhancement is achieved through changing the concrete's characteristic failure mode, from brittle to that of a pseudo-plastic nature through the addition of fibres [6].

On consideration of the fibre types added to concrete, synthetic fibres exhibit similar functional characteristics to that of steel fibres by bridging cracks formed in concrete due to external actions, however the mechanical properties of steel and synthetic fibres are very different and this is pertinent when considering the post crack performance of fibre concrete. This performance difference between fibre types accounts for the need to individually

* Corresponding author.
E-mail address: alan.richardson@northumbria.ac.uk (A. Richardson).

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proportion fibre quantities to achieve equitable post crack flexural performance [9]. This research builds on the performance data comparison of steel and synthetic fibres when subject to impact forces [8]. Predicting how a concrete element will perform when subject to impact, still remains an area which is not well understood [3]. The plain concrete slabs within this test were set as a base line for performance. The fibre concrete performance was a measured change from the established baseline measurements This paper seeks to contribute to the understanding of the most effective fibre mix available to provide impact/ballistic protection.

1.1. Impact analysis on concrete structures

Impact by a high speed point load, such as a bullet, has similarities with a small standoff blast [7] and this has informed the test methodology as shown in Fig. 2. An explosion near a concrete wall causes a high speed compressive stress wave to load the front face of the wall [7], resulting in initial front face spalling Almansa and Cánovas [1]. A significant proportion of the energy will travel through the wall as a compressive stress wave [7] and a small proportion of this energy will be reflected, causing a tension rebound from the back face. It is this tension rebound that can cause the back face to spall [7].

Back face spalling is an important consideration in protection of the public against shrapnel injuries occurring from concrete fragmentation and spall when explosive forces act on concrete structures [4]. The extent of injuries resulting from spall has been investigated by de Ceballos [5] who found that 36% of injuries in the Madrid Metro Bombings in 2004 were shrapnel wounds, caused by projectile material. Irrespective of whether explosions produce projectiles that ultimately penetrate a structural concrete and compromise its integrity (demonstrating back-face spalling on penetration through the back face), initial spall is promoted by tension exerted on the back face under the speed of the compressive stress wave. The equilibrium response to this impact forces concrete particles to be ejected from the back face of the structure. This is shown in Fig. 1 (adapted from Millard et al. [7]).

Coughlin et al. [3] note that while concrete is commonly used for blast resistance due to its high mass per unit cost, the brittle nature of concrete means it is prone to spalling and fragmentation. Normal reinforced concrete does not perform well when subject to impact or explosion loading [7] as it is inherently weak in tension [2]. Sukontasukkul et al. [11] define concrete as a quasi-brittle material, which when subject to loading beyond its tensile strength, usually fractures. Concrete is often reinforced with steel, to cater for the tensile strength deficiencies. However, Coughlin et al. (2009) note that blast loads can still damage both reinforced and unreinforced areas of the concrete structure. Millard et al. [7] suggest that when failure occurs at the surface of a concrete wall subject to blast, the presence of conventional steel reinforcement will generally not prevent the wall from material spalling (see Fig. 2).

Conventional steel reinforcement bars do not prevent the concrete failing from the stress force induced by the tension rebound, as these bars merely act as obstructions within the dominance of the concrete matrix and are therefore inherent areas of weakness [7]. It is suggested that fibre concretes, produced by randomly dispersing thin fibre elements throughout the concrete matrix, may

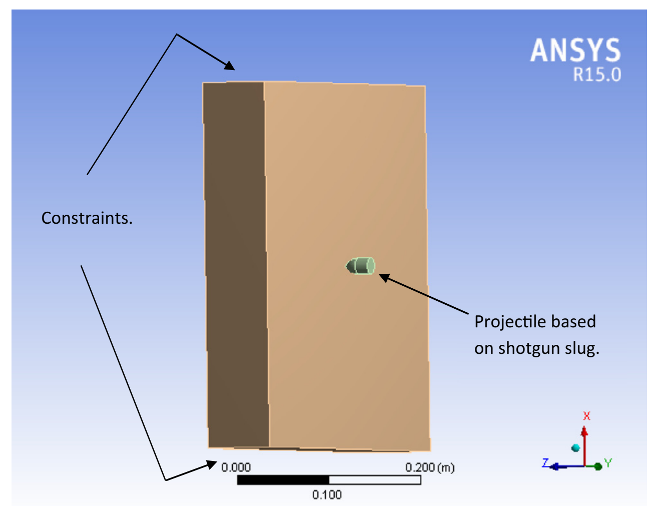

Fig. 2. FEA model for a 400 mm × 400 mm × 75 mm concrete slab.

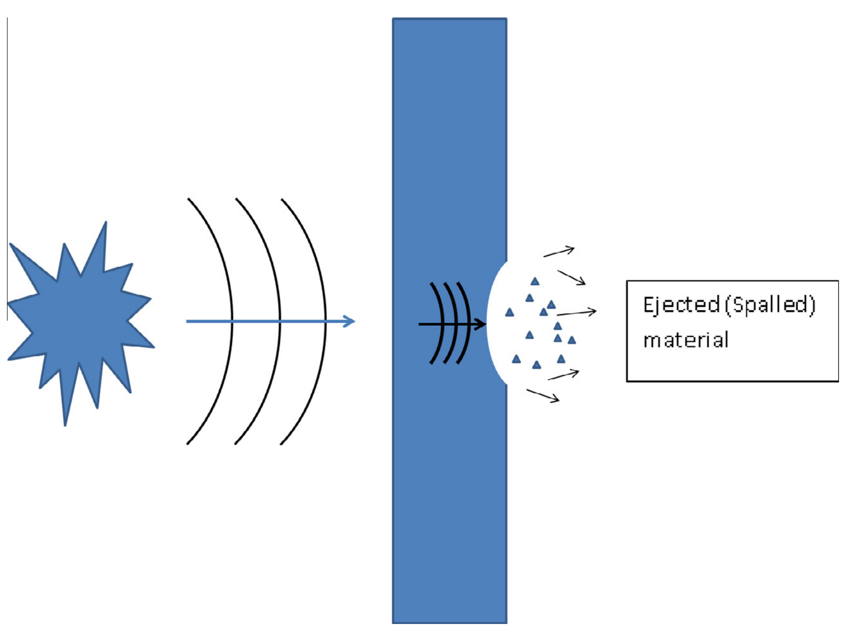

Fig. 1. Compressive stress wave causing spalling to rear face (adapted from [7]).