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Improving the performance of concrete using 3D fibres

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Abstract

This paper examines whether 3D fibre reinforcement can improve the toughness and flexural strength of concrete, when compared to equal dosage of straight steel fibres. This work was carried out to determine structural qualities that may lead to potential enhanced performance when concrete is subjected to a bomb blast and in addition the same structural qualities may act as a safety measure in earthquake situations. The majority of injuries caused from bomb attacks are a result of fragmented building components energised by the blast wave, therefore it is vital to reduce fragmentation of concrete. It is known that fibre reinforcement can reduce fragmentation of concrete by increasing energy absorption. A three point beam test was conducted on two batches of beams reinforced with straight steel and 3D fibres respectively, so that flexural strength and post crack toughness could be calculated and compared. A paired comparison test was carried out between the straight steel fibres and the 3D fibres. 3D and straight steel fibres were also embedded in cubes, so that pull out testing could be conducted and compared for the two fibre types. 3D fibre reinforced samples proved to have a higher flexural strength and post crack toughness than straight steel samples. 3D fibres also had a much higher pull out value. After testing, 3D fibres continued to span the rupture plane after initial crack formation during 3 point bend testing, which held together the concrete matrix.

These findings suggest 3D fibre reinforced concrete would perform better as a blast protection material when compared to straight steel fibre reinforced concrete, as the results show 3D fibres produce tougher concrete that hold together fragments after loading.

Keywords: Fibre reinforcement, concrete, blast loading, toughness, earthquake, three point bend test, fracture, pull out.

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1. Introduction

Modern society has accepted a culture where buildings are constructed in a way that leaves them vulnerable to bombing attacks. This was tragically highlighted in the 1995 Oklahoma bombing which caused nearly 700 people injuries and cost 168 lives [1]. This incident demonstrated how vulnerable the structure of the targeted Alfred P. Murrah Federal Building and other surrounding buildings were. The American government responded by erecting Jersey barriers (Figure 2) around prominent federal buildings in the weeks that followed. The poor performance and vulnerability of the bombed buildings illustrates the need for this investigation into how building material performance can be improved with regards to being subjected to a bomb blast. As concrete is the most common building material worldwide, this paper will introduce the idea of fibre reinforcement, as it is seen as a way of increasing concrete energy absorption and subsequent performance in a

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bombing attack. Injuries sustained by bomb attacks can be categorised in four main ways. Primary; caused by exposure to the blast wave. Secondary; penetrating injuries caused by objects or building components energised by the blast wave. Tertiary; caused by people being displaced / thrown by the blast wave. Quaternary; injuries caused by building collapse or exposure to hazardous chemicals caused by the blast [2].

Typically, when an explosion occurs adjacent to a 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 [3]. 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 [4]. 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 fragments and cracks [5]. It is hoped 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 & Atkins [6] 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, [7] state that shrapnel wounds accounted for 36% of all injuries. Evidently there is a requirement to reduce concrete spalling and cracking, so that the material does not fragment creating lethal projectiles.

2.0 Blast Protection

There are two main ways of providing blast protection. These are defined as "hard and massive" and "ductile and dynamic" [8]. Hard and massive systems work by being large and dense enough to withstand damage caused by a blast, whereas ductile and dynamic systems include such things as fibre reinforced concrete (FRC) and other systems with high energy absorption and toughness values. Hard and massive systems are used by military engineers, and include the likes of HESCO, Alaska and Jersey barriers (See Figures. 1. & 2.). However, these hard and massive systems are "not a practical answer to commercial buildings" [8], whereas ductile and dynamic FRC may be a better option.

Fig. 1. Blast protection HESCO [9]

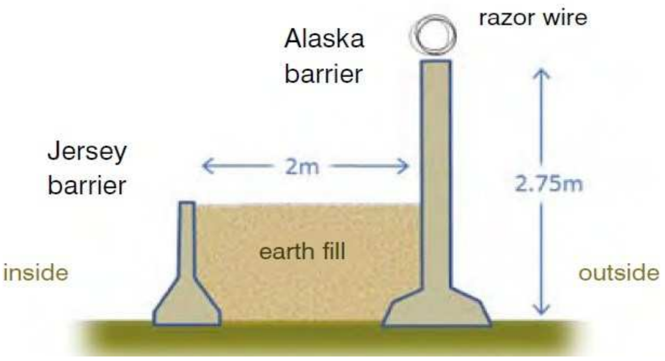

Fig.2. Alaska and Jersey Barriers. [10]

Matten [10] explains that in early 2008, British forces in Basra (Iraq) came under increasing attack from rockets and mortars containing up to 25kg of high explosives, "blast and fragmentation protection was therefore vital". If fibre reinforced concrete (FRC) reduced spalling and fragmentation due to high levels of toughness, it may be useful in providing force protection, and reduce secondary injuries resulting from energised fragments. Matten [10] goes on to state that "permanent reinforced concrete structures offer the very best protection against rocket attack", and where several bed spaces were subjected to rocket attacks, those protected with dense concrete blocks resulted in only minor injuries. This supports the argument for the development of new reinforced concrete materials as force protection. However, Hayhurst, [11] highlights the importance of identifying 'threat', and matching protection materials accordingly. He points to the danger of "over matching performance to threat". For example, his experience of poorly reinforced concrete blast barriers 'disintegrating', providing little protection from blasts at entrances to check points, and well reinforced, high energy absorbing barriers, being displaced by the blast, injuring or killing those in their wake. Using FRC technology to create an element that can withstand a blast may not be what is required, it could be an ‘over match’, too strong / tough an element causing comparable human casualties if displaced by a blast. Therefore the anchorage of these protection measures is critically important and an integral part of safe design.

There is a heavy reliance on ‘HESCO’ (Fig.1.) at present in the war theatre (2012). “HESCO has delivered approx 90% of force protection capability in Iraq since 2003” [9]. At present concrete is not seen as a viable blast protection material. In its current application in Afghanistan (as a ‘hard and massive’ system) it must be precast in large elements for it to offer blast protection, and transported from Kuwait. This is expensive and presents logistical issues; due to the size and weight of the concrete elements, few can be transported [11]. The view that FRC technology could be used to create lighter panels or blocks to offer blast protection in theatre is one shared by Sheridan [12]. Fibre reinforcement could offer a solution by allowing lighter, more transportable, FRC components to be cast with the same energy absorption and blast protection values as current ‘hard and massive’ systems.

Filling HESCO can be a tedious and time consuming task. In the absence of a JCB it took the men of 3 Troop, 26 Armored Engineer Sqn “1152 trips and three nights” to fill sixteen HESCO containers by hand on Operation Herrick 14 (Afghanistan) explains Taylor [13]. Pre fabricated lightweight FRC, manufactured into blast walls, may have been a less time consuming, and a more permanent solution.

FRC systems could be incorporated into the design of Embassy and Government buildings as well as other such buildings under the threat of bomb attacks. Considering blast protection early in the design stage is important, “typically blast protection added at the design stage adds between 0 and 5 per cent to overall construction cost” [8]. This shows that blast protection is affordable and represents a cost effective way of managing risk.

3.0 Earthquake engineering

During an earthquake, buildings are often subjected to cyclic loading which results in fatigue fracturing. After the 2011 Christchurch earthquake the government funded Earthquake Engineering Field Investigation Team (EEFIT) deployed to New Zeeland to investigate the event. Reporting that of the 50% of buildings classified ‘usable’ the majority were reinforced concrete, and that due to the poor performance of unreinforced masonry most of the city’s historic buildings will now be demolished [14]. Reinforced concrete was better at dissipating the earthquakes energy and transferring it through ductile load paths to the ground [14]. FRC is also good at transferring and absorbing energy, so could have applications with regard to Earthquake technology design. When a building collapses due to an earthquake, casualties and fatalities are greatly compounded. Coburn [15] states that, “Structural collapses are responsible for 75% of deaths in earthquakes”. This demonstrates a clear need to improve concrete performance, fibre reinforcement is thought to be able to increase the ultimate limit state (ULS) of concrete elements, this could increase the loading a building can sustain before collapse and therefore could save lives.

FRC could be used for concrete elements such as beams and columns for buildings in earthquake prone locations, due to its high energy absorption properties. In the late 1990’s steel fibre reinforced concrete encased steel truss members were designed, for use in earthquake prone buildings [16]. Gustavo et al, [17] built upon this work when researching into the development of an earthquake resistant framing system. Gustavo et al, [17] proposed a hybrid FRC and steel truss system as a solution, in testing the hybrid FRC elements, they showed an “excellent energy dissipation capacity” and are said to have performed well. This suggests that FRC has a place in future earthquake resistant building technology, however we need to determine the best fibre type or the best hybrid mix of fibres. Fibre reinforcement can be used and may reduce injuries caused by energised fragmentation as well as providing additional time for escape with regards to earthquake resistant structural design.

4.0 Steel fibre reinforcement

An advantage of steel is its similar thermal co-efficiency to concrete, and most steel has ductile properties, therefore it lends itself well to absorbing energy. Steel fibres vary in size and diameter. Some fibres come with hooked or spade ends to increase the bond strength with concrete. Steel fibres can be classified in one of five categories outlined by BS EN 14889-1. These are as follows; cold drawn wire, cut sheet, melt extract, shaved cold drawn wire, and milled from block.

The fibre bond is developed as water evaporates from the concrete mix and the concrete shrinks and therefore grips the steel - this is termed as a “mechanical bond” [18].

A drawback of steel reinforcement is its susceptibility to corrosion if not properly treated with a rust proof coating or embedded in a sufficiently alkaline mix of concrete. Richardson and Drew [19] explain that corrosion of steel reinforcement in concrete structures can compromise structural stability and create major maintenance problems. It is extremely important to protect steel reinforcement, as corrosive conditions could severely deteriorate a structure if constructed with steel reinforcement [20].

A consideration when using closed loop 3D steel fibres is the bond strength of welding. Thomas et al. [21] highlight this point stating that “in welded components, the toughness of the joint is of great concern”. If the weld is not as strong as that of the steel used to manufacture the fibre, its strength and toughness could be compromised, however the weld would have to bridge the rupture plane and the lap weld length is small when compared to the overall length of the 3D steel fibre.

The likelihood is that reinforcement will be provided in x, y and z planes cannot be guaranteed by adding 2D fibres to the concrete mix. It could be argued that for this reason traditional setting out of steel bars is more reliable and accurate. Stahli & Mier, [22] discuss the tendency for steel fibres to align themselves with the mould walls, which may skew small scale test results.

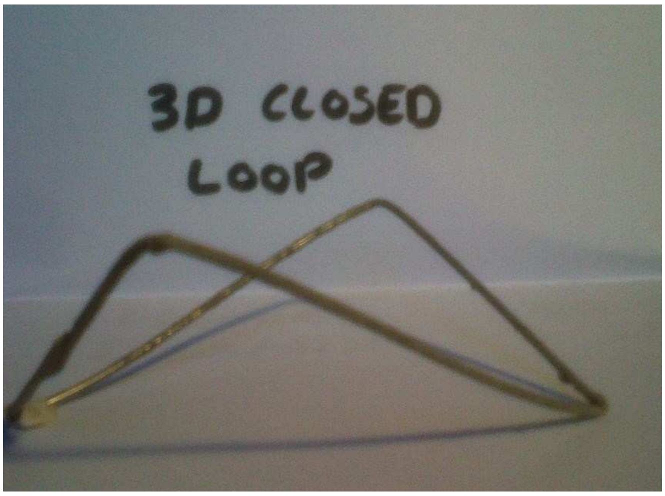

Figure. 3. - 3D Closed loop fibre.

Closed loop steel fibres can be bent and shaped into 3D steel fibres, as shown in Figure 3. This way, no matter how the fibre is situated in the concrete it will offer reinforcement in the x, y and z planes. Load is transferred through “the pinning action of aggregate” [23] this is where aggregate in the concrete mix is gripped between two closed loop fibres and the load placed on the beam is transferred across the fibres through the aggregate, Commenting on 3D closed loop fibres, Thomas et al. [23] explain that in a closed loop fibre reinforced system “there are no redundant elements – those that are not in tension in one direction provide secure anchorage in another direction”, “when the structure is subjected to multi axial tension, the elements of closed loop fibre reinforcement can simultaneously provide both tensile reinforcement and anchorage”. The aggregate between fibres acts as an anchor, reducing the likelihood of the bond between fibres and concrete breaking or causing ‘pull out failure’.

5.0 Materials

5.1 Mix design

The mix design as shown in Table 1 was chosen for the concrete being tested due to the need for sufficient cement paste to coat the fibres:

Table 1. Mix design

Material	Quantity (per m³)
Cement (CEM 11) (42,5 N)	400kg
Sand < 4mm	690kg
Coarse aggregate <20 mm	1120kg
Fibre dosage	25kg
Water cement ratio	0.45

5.2 Fibre Reinforcement

The materials used as reinforcement for testing were as follows; (2D fibres) 50mm length, 0.889mm diameter high tensile steel straight fibres with offset ends, with a tensile strength of 1100Mpa, and (3D fibres) 230mm perimeter, 1.218mm diameter lap welded closed loop chromium alloy steel 3D fibres, with a tensile strength of 650Mpa as Figure 3. A fibre dosage of 25kg per m³ was used for both types of fibre reinforcement.

5.3 Concrete

The concrete used for the manufacture of test beams and cubes was a C35 characteristic design strength at 28 days of curing time, with a 60mm slump. The cubes and beams were cured in a water filled tank at 20°C with a Ph value of 10.2 to prevent leaching of the samples. The dimensions of the cast specimens were 150mm cubes and 500mm x 100mm x 100mm beams.

6.0 Methodology

The test programme is outlined in Figure 4.

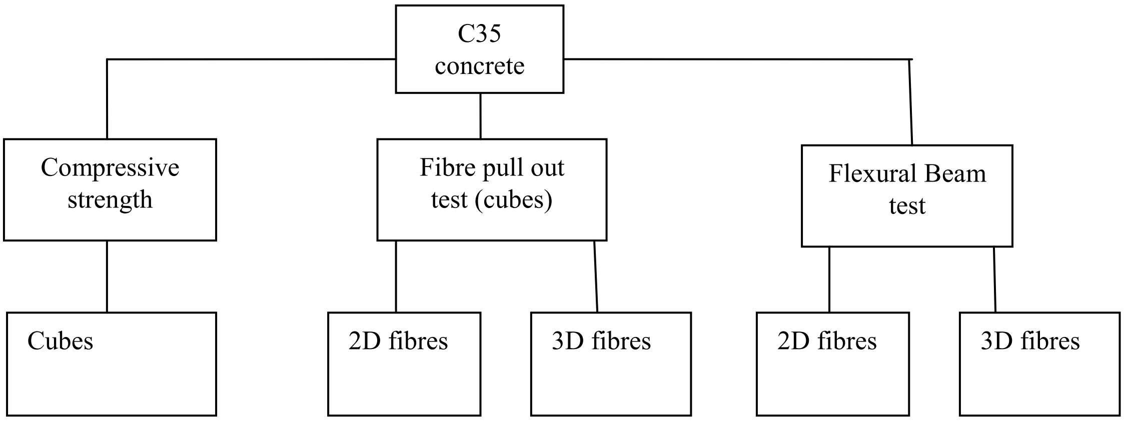

Fig.4. Test programme

Cubes were fixed into the Lloyds testing machine. The fibres clamped and the cubes anchored, as shown in Fig. 5. The machine was then operated to pull the fibres from the cube, with the point of fibre pull out/or fibre failure being recorded, as well as the maximum load.

Fig. 5. Arrangement of Lloyds testing machine displaying pull out testing.

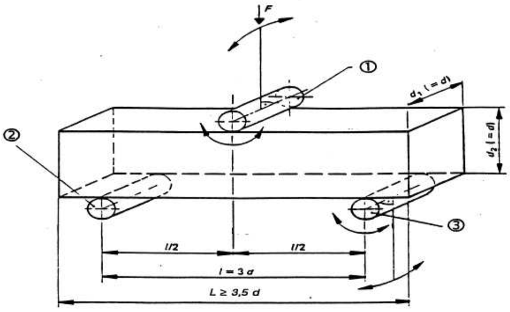

Fig. 6. Arrangement of loading of test specimen, centre-point loading (British Standards Institution, 2004).

Concrete beams of dimensions 100mm x 100mm x 500mm were loaded into the test apparatus in the arrangement shown in Fig. 6. Testing was conducted in accordance with BS EN 12390-5:2000, with the distance between the two supporting rollers set at 300mm and the Lloyds testing machine applied a rate of strain at 2.2mm/min.

In order to determine flexural strength of the beams, the load was applied to the beam until the occurrence of the first crack, which was recorded. Loading continued to be applied to the point of total failure (peak load), which was also be recorded. The process was repeated for all three straight steel fibre reinforced beams and all three 3D steel fibre reinforced concrete beams.

Load and deflection charts were used to determine the relationship between the area under the graph up to the first crack, which was then divided into the total area under the load deflection line. This was taken to a maximum of 10.5 times the initial deflection at the first crack as shown in Figure 7 (ASTM 1018:1997).

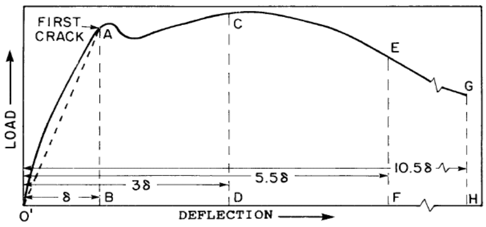

Fig. 7. – Load deflection chart (ASTM 1018: 1997)

7.0 Results

7.1 Compressive strength

Table 2 displays the compressive strength of the concrete cubes, taken at 28 days. All failure modes were satisfactory and in accordance with BS EN 12390-3:2009.

Table 2. Compressive strength test results.

	Cube	**Compressive strength (N/mm²)**	**Mean value (N/mm²)**	**Standard deviation**
Compressive Strength	1	42.2	41	1.25
	2	39.7		
	3	41.1		

7.2 Pull out test

Pull out testing was conducted on six cubes, three with straight fibres half embedded into each cube. Three with 3D fibres half embedded, so that the pinning action of aggregate between the 3D fibres could be tested. The pull out values were consistent displaying a small standard deviation and they showed 3D fibres to have a greater pull out value than the straight fibres. Mean pull out values were calculated and are displayed in Table 3.

Table 3. Pull out test results

	Cube	**Peak load/pull out failure (N)**	**Mean value (N)**	**Standard deviation**
Pull Out	Straight 1	587	610	21.73
	Straight 2	630		
	Straight 3	614		
	3D 1	2220	2170	56.58
	3D 2	1990		
	3D 3	2300		

Table 3 shows the mean peak loading for straight steel fibres to be 610N, and the mean peak loading for 3D fibres to be 2170N. The 3D fibres transferred 356% more force to achieve ‘pull out’ failure of a 3D fibre, compared to the force required to ‘pull out’ a straight steel fibre. The relationship between the straight and 3D fibre pull out is complex and not easily equated. However these results provide an indication of a single fibre length crossing the rupture plane and its expected anchorage. What is not easily evaluated is the number of straight fibres that will be effective in transferring a post crack load, the number of fibres found crossing the rupture plane has been low in previous tests.

7.3 Post crack toughness

The load applied to the beam was plotted against the deflection, the peak loading was recorded and deflection continued to be plotted against load until it was 10.5 times that of the deflection at peak load (in accordance with ASTM 1018) as shown in Fig. 8 and 9.

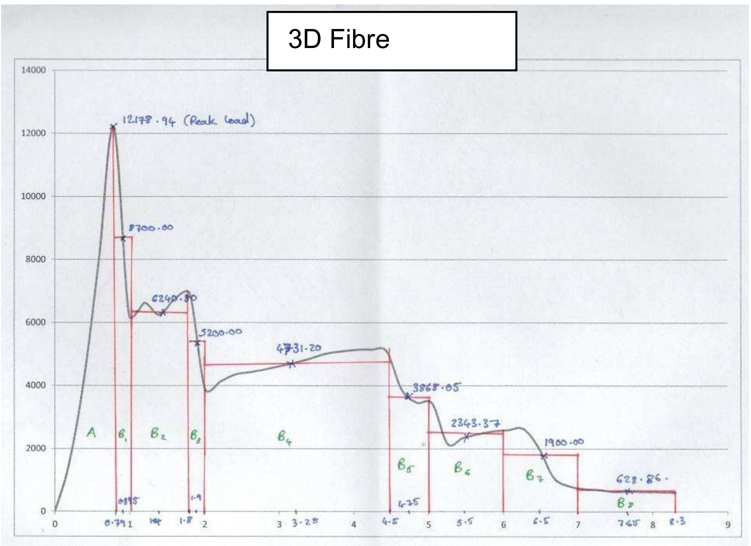

Fig 8 – Representative load deflection chart for 3D fibre

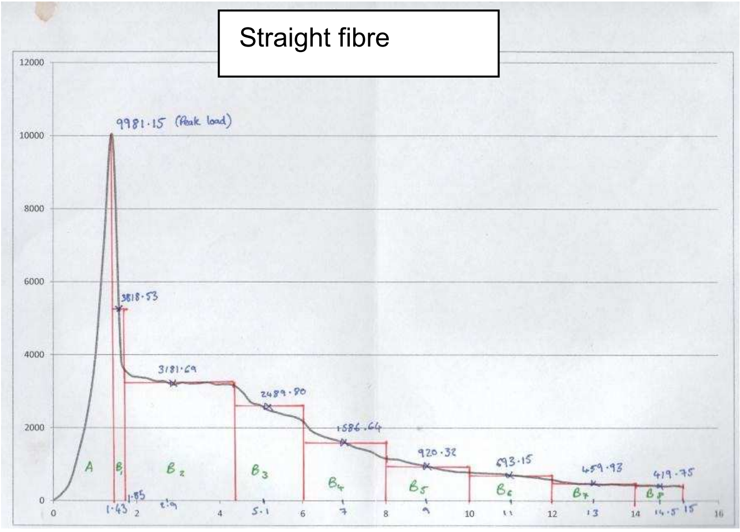

Fig. 9. Representative load deflection chart for 2D fibre

Mean post crack toughness was then calculated for each beam type and is displayed in Table 4.

Table. 4. Post crack toughness results

	Beam	Post crack toughness value	Mean value	Standard deviation
Post Crack Toughness	Straight 1	4.06	4.7	0.86
	Straight 2	4.68		
	Straight 3	5.27		
	3D 1	10.12	8.4	1.79
	3D 2	8.64		
	3D 3	6.55		

Analysis of the results shown in Table 4 indicate that beams reinforced with 3D fibres were 178% ‘tougher’ than those reinforced with straight fibres. This increase in performance was remarkable given the steel used for the 3D fibres was weaker than the straight steel fibre and the perimeter to cross sectional area was lower for the 3D fibres, which gave the straight fibres additional steel surface for a given weight in the concrete mix.

7.4 Flexural strength

The maximum load to initial concrete beam failure was recorded. The mean flexural strength was then calculated in accordance with BS EN 12390-5:2000 for each beam type and the results are displayed in Table 5.

Table. 5. Flexural strength results

	Beam	Flexural strength (N/mm²)	Mean value (N/mm²)	Standard deviation
Flexural Strength	Straight 1	4.49	3.73	0.70
	Straight 2	3.61		
	Straight 3	3.08		
	3D 1	3.92	4.50	0.85
	3D 2	4.11		
	3D 3	5.48		

The standard deviation for each beam type is similar in each case and the additional flexural strength displayed when comparing the straight and 3D fibre results show an increase in flexural strength of 21% in favour of 3D fibres.

8.0 Conclusion

At an equal fibre dose, the 3D fibres outperformed the straight fibres in every area under examination. The results are very encouraging, as the straight fibres pulled out and the 3D fibres snapped, which displayed a high bond strength. If the steel had been of equal strength the 3D fibres would have displayed much higher pull out and flexural strength values.

It is strongly recommend that the test be repeated with equal strength steel and equal diameter steel and in addition, beams be cast to examine impact energy absorption using 3D fibres. This test was limited due to the supply of the novel 3D fibres. A larger scale test should be carried out to provide data of a greater statistical significance.

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9.2 Appendix

HESCO Bastion Ltd is a leader in the design and manufacture of rapidly deployable barrier systems. Established in 1991, HESCO has been developing and manufacturing the innovative Concertainer® units for the purposes of military protection, critical asset protection and flood protection.