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

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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.

Key words: Impact, flexural toughness, hybrid synthetic fibres, ballistic.

1.0 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 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 Cha-Don 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 & 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.

2.0 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 400kg CEM 1 cement (42.5 N), 40 kg silica fume, 731kg coarse sand (<4mm), and 1057kg of 10 to 16mm 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 manufacture process. Most suppliers quote the tensile strength of their fibres in their respective literature; and most fibres on the market today range from 400-600MPa [3].

Table 1 displays the basic properties of the fibres used herein.

Fibre type	Dimensions mm	Material	Aspect ratio
Dove Tailed 20	2 x 60	polypropylene	30
Type A	50 x 0.941	polyethylene	53.1
Type B	50 x 1.183	polypropylene	42.3

Table 1 – Fibre types

2.2.1 Dovetailed cross section fibre (DT)

The fibres tested herein are different in size shape and material composition; three fibres are tested; one of which makes use of a dove tailed (DT) fibre shape where the stretching and diameter change produces a gripping effect in the fibre dovetails and this permits greater stress transfer once the initial bond is broken. These fibres are referenced DT (Dovetail fibres). This DT fibre technology is compared against two different synthetic structural Type 2 fibres. The variables of the Type 2 fibres were, length, profile, polymer type and cross sectional area. Due to the complex shape of the fibres, the nominal diameters of the fibres are stated, not taking into account the undulations or dovetail features, both of which can provide additional load transfer beyond the first sign of fibre slippage when under load.

The pulltruded polypropylene DT fibres were 2.0mm diameter and 60mm in length and manufactured from polypropylene having a modulus of elasticity of 3500 N/mm^2. This fibre has the same material properties as Type B fibres used within this research. The design makes use of the contraction of the fibre material to enhance the fibre to cement paste mechanical bond when a tensile load is applied. The gripping effect is shown in Figure 1 when the polypropylene fibre is under load, and the black arrows indicate a gripping effect due to the Poisson effect. This was measured in Richardson et al [2].

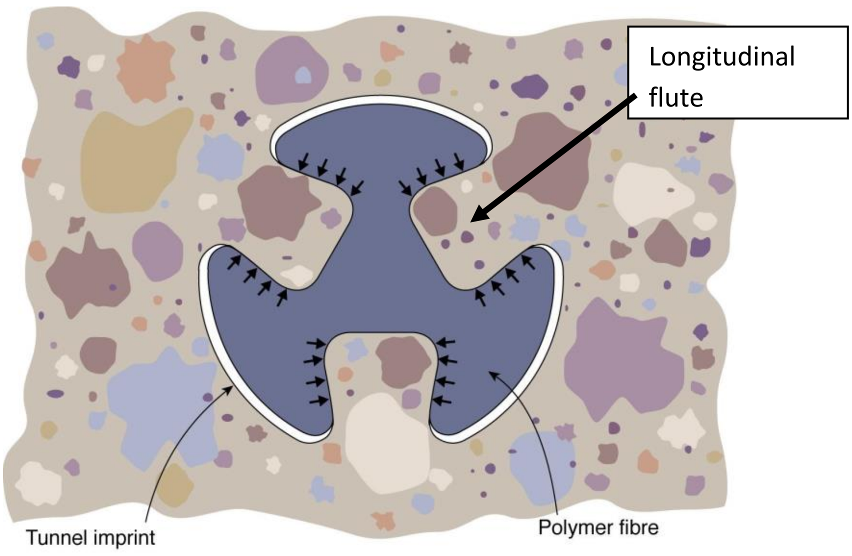

Figure 1 - Cross sectional area of DT fibre under load. (Source [21])

Figure 2 shows the end detail of the DT fibre at x 100 magnification. The dovetail fibre features are clearly visible within Figure 2 and as the inset design detail by Thomas et al [21]. The DT fibres can be used as a direct replacement for other synthetic fibre types in concrete.

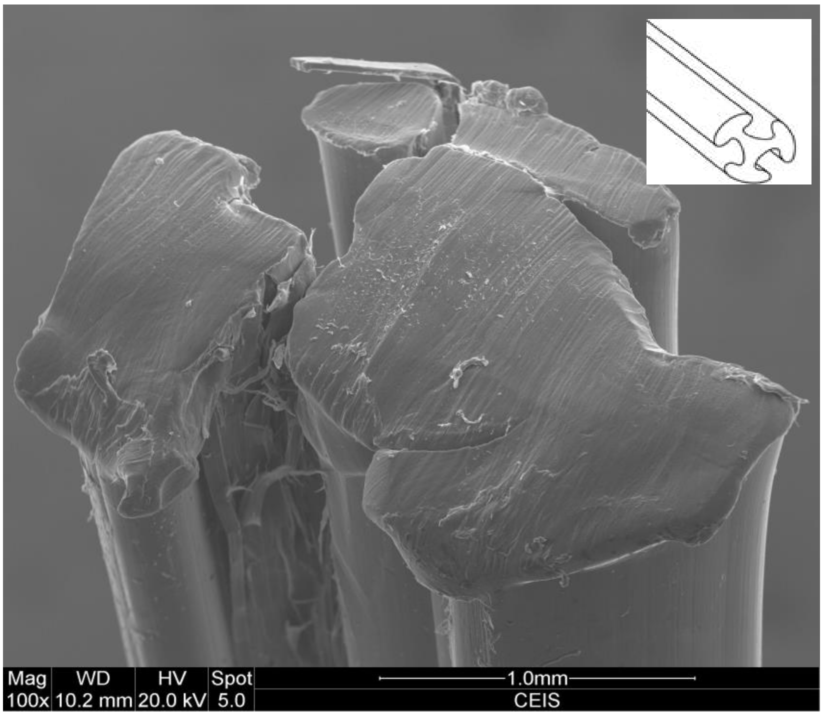

Figure 2 - DT fibre 2mm diameter (Inset source – [21])

2.2.2 Comparative fibre details (Types A and B).

Two different structural fibre types were used in conjunction with the DT fibres to compare against the DT fibres, as well as to compare the relative performance between themselves.

The indented/crimped fibres (A) are 50 mm x 0.941 mm nominal diameter polyethylene macro-monofilament Type 2 fibres that have a melting temperature of 164 °C and an elastic modulus of 5000 N/mm^2. The fibre end showing the longitudinal profile and cross sectional area, are displayed in Figure 3 at x100 magnification.

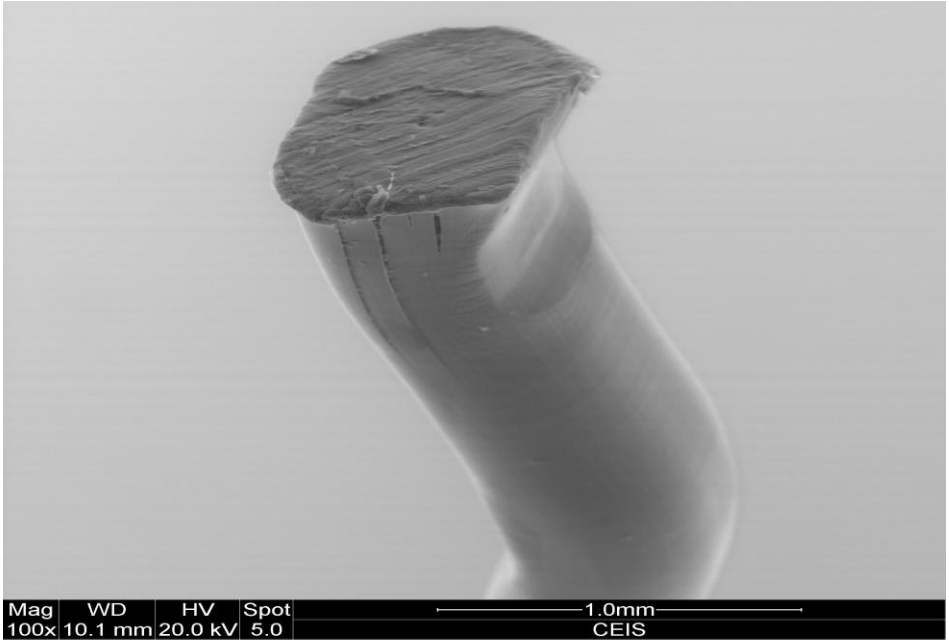

Figure 3 – Fibre “A” polyethylene fibre showing end and fibre profile details

The crimped fibre (B) was composed of polypropylene had the following physical properties: specific gravity 0.91, fibre length 50 mm x 1.183 mm nominal diameter, elastic modulus 3500 N/mm^2, and a melting temperature of 175 °C. The fibre end displaying the longitudinal profile and cross sectional area is shown in Figure 4 at x100 magnification. Fibre B was manufactured from the same polypropylene material source as the DT fibres, for the purpose of direct comparison.

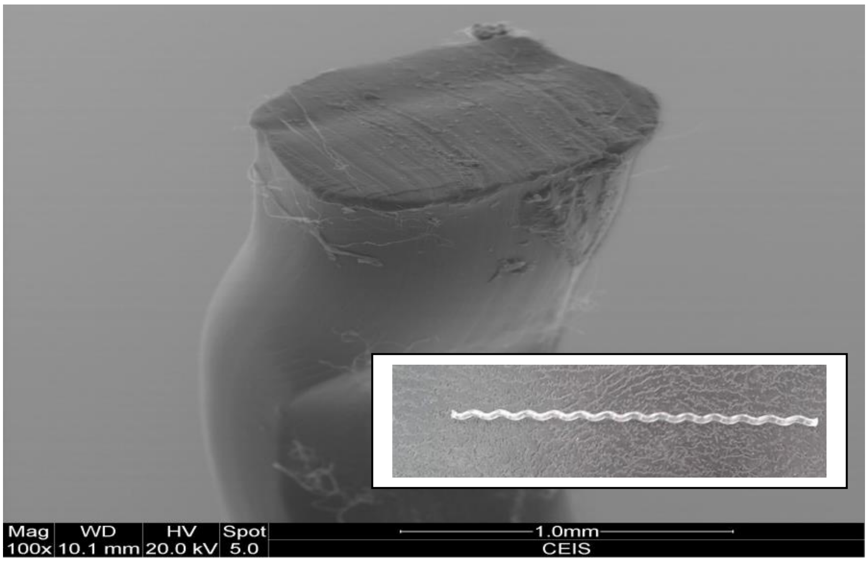

Figure 4 – Fibre “B” polypropylene fibre, end and fibre profile detail

2.3 Fibre dosage

The density of polymeric fibres is of the order of 900 - 950kg/m^3. Typical dosages vary up to a maximum of about 12kg/m^3 in concrete which is approximately equivalent to 13.5% by volume. The manufacturer's normal maximum dosage for fibres A and B was 7kg/m^3 to achieve crack free conditions in ground supported floor slabs. Previous research conducted using 1.3mm DT fibres, was carried out with a 50kg/m^3 DT fibre addition [21]. The fibre dose for this test was reduced to 20 kg/m^3 because of difficulty in forming a fair face to the concrete with high fibre doses. There was also a cost implication using many fibres in the concrete mix. The strength of the concrete used herein was increased from the concrete used within the Thomas et al test [21] to provide a wider range of comparative data.

3.0 Test methodology - Dove tailed fibre technology

The manufacturing process entailed the use of 6 No 100mm x 100mm x 500mm beams, for flexural strength and load/deflection analysis and 6 No 100mm x 100mm x 425mm beams for impact testing. Twelve beams for each concrete type batch were produced and 3 cubes were taken from each batch to evaluate the compressive strength. Two 400mm x 400mm x 50mm concrete slabs were cast of each concrete type for rifle fire ballistic testing. The overall test programme is outlined in Figure 5.

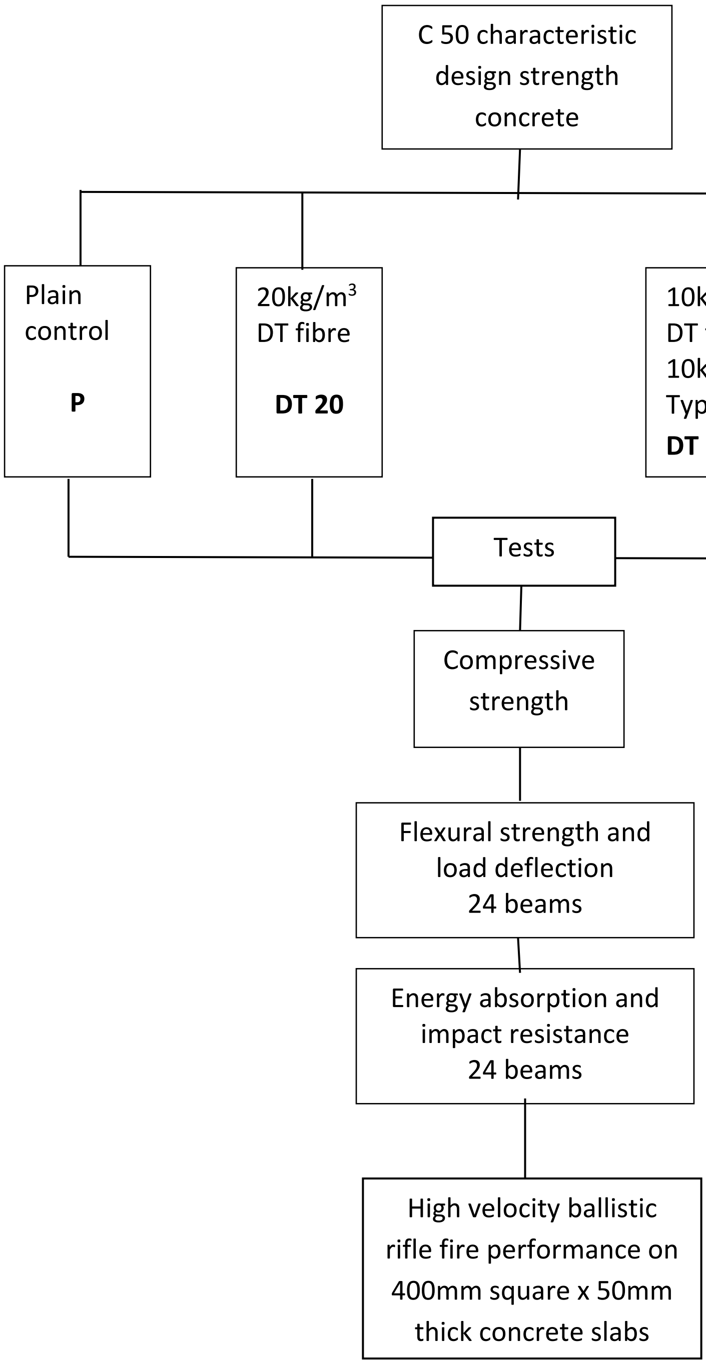

Figure 5 – Test programme.

A rotary drum mixer was used to batch the concrete and a vibrating table was used for compaction purposes. Following the pilot mixing of the first batch of concrete it was noted that fibres remained in the cement slurry attached to the rotary mixer drum. Dependant upon the fibre type approximately 2% to 10% of the fibre dosage remained in the mixer once the mixer was emptied.

The concrete containing smaller fibres (A) had the greatest loss, whereas the largest fibres (DT) recorded the smallest drum retention. Care was exercised to empty the rotary drum thoroughly during the batching.

3.1 Sample preparation

The beams were marked for identification, de-moulded after 24 hours from casting and placed in a curing tank at 20°C with a pH value of 11 to prevent leaching of the samples for a period of 28 days. The 500mm beams had a 5mm deep saw cut across the bottom face of the beam to form an induced crack and cut through the fibres lining the mould. The 425mm and 500mm beams were tested using the two opposing cast faces as the top and bottom faces, ensuring good contact with the supports and the drop hammer (tup) or loading head. The slabs had a surface trowelled finish and were tested at 21 days of age.

3.2 Test apparatus

Toughness analysis was carried out to BS EN 14651:2005+A1:2007 [28], and all of the load/deflection charts were converted to load/ crack mouth opening deflection (CMOD) charts for every beam tested. The charts were used to calculate the limit of proportionality (LOP) values and crack mouth opening deflection ($CMOD_j$) values. LOP describes the flexural strength of a specimen at point of first crack while $CMOD_j$ describes the residual post crack flexural strength of a specimen at a given point. The four points of measurement are shown below:

- $CMOD_1$ = 0.5mm (minimum permitted value of 1.5 N/mm^2)
- $CMOD_2$ = 1.5mm
- $CMOD_3$ = 2.5mm
- $CMOD_4$ = 3.5mm (minimum permitted value of 1.0 N/mm2).

Using the Lloyds LR100K apparatus a load was applied to the beam through a three point loading frame at 0.05 mm/min as shown in Figure 6, until the CMOD reached 0.5 mm then the rate was increased to 0.2 mm/min until ultimate limit state was achieved or a pre-determined cut off point reached.

ASTM 1018 was one of the previous methods for calculating toughness of concrete, which is no longer current. Vellore, Golpalaratham and Gettu [26] state that, “most standards are comparable, ACI 544 uses a ratio of load/deflection curve so does ASTM 1018, which is essentially the same”, however the limiting deflection analysis in ASTM 1018 [27] was considered a most useful quality for a paired comparison test. The test was terminated at around 10.5 times the deflection of the first crack in accordance with ASTM 1018 as further loading produced unrealistic deformation.

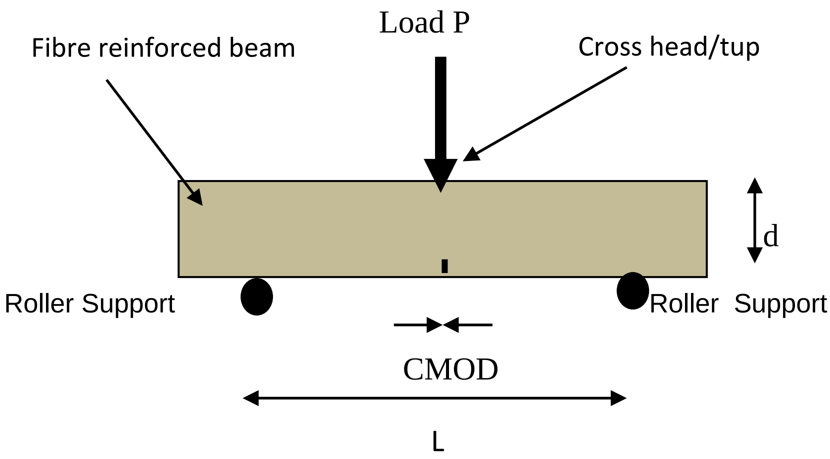

Figure 6 – Beam loading arrangement

3.3 Impact testing

The loading arrangement was the same as the Lloyds apparatus for the Instron CEAST 9340 apparatus. The Instron CEAST 9340 apparatus is essentially a drop hammer with a half round striker bar (tup). The beams were subject to a single impact using a standard weight of 10.032 kg. The drop height had to be determined using a pilot study to establish the height required to create a rupture plane in the beam, thus allowing more energy to be released than was being absorbed, subsequently propagating a crack in the beam.

3.4 Rifle fire ballistic testing

The purpose of the ballistic testing was to compare the comparative performance of fibre concrete against plain concrete. The parameters examined were overall slab integrity, entry and exit apertures, distance concrete ejected following impact and cone failure details. Impact by a high speed point load, such as a bullet, has similarities with a small standoff blast [29] and this informed the test procedure.

Concrete when used generally in construction is often reinforced with steel, to give the reinforced concrete the tensile strength it requires for the required application. However, blast loads can still damage both reinforced and unreinforced areas of the concrete structure.

The mechanism for 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 spall. An explosion near to a concrete wall causes a high speed pressure wave to load the front face of the wall [29]. A small proportion of this energy will be reflected back, while a significant proportion of the energy will travel through the wall as a compressive stress wave [29].The reflection of the compressive stress wave within the concrete causes a tension rebound from the back face; it is this tension rebound (brisance) that can cause the front face to spall.

Slabs were supported vertically at two points (top and bottom) and a high velocity rifle was used with a muzzle exit speed of 914 m/s (3290 km/hr). The bullets used had a mass of 180 grains (11.66 grams). The bullets were composed of a copper jacket with a lead core and used 66.6 grams of explosive powder to discharge the weapon. The rifle was discharged 100m from the target (concrete sample) which was a close as could safely be carried out with regard to ejected concrete particles and a maximum distance to minimise velocity degradation. The travel time from gun to target was 0.109 of a second and the drag force was 9.68 N. These values would produce a negligible deceleration over the distance the gun was discharged from the target. The anticipated kinetic energy at impact was 4891 Joules or Newton metres. The bullet shaped was pointed and this provided a very concentrated point load as shown in Figure 7.

Figure 7 – Bullet details

4.0 Results

4.1 Compressive strength

The 28 day compressive strength test was undertaken to BS EN 12390-3:2002 [22] and the results are displayed in Table 2. The DT 20 cubes had a dosage of 285% more fibres inclusion than adopted by most manufacturers' maximum addition. From earlier work conducted to establish the relationship between fibre addition and compressive strength, Richardson [23] showed that as the fibre dose or volume increased, the compressive strength decreased. This earlier study utilised a low to medium strength concrete of grade C35. The DT 20 concrete is a high strength concrete and the combination of fibres in this concrete matrix does not appear to adversely affect the compressive strength value realised in the test. The compressive strength of the concrete may marginally affect the pull out values of the fibres due to the degree of bond available. If a high strength concrete is used, the fibre concrete may be classed as a brittle material [24] rather than a quasi ductile material when used at lower strengths and the fibres will snap rather than pull out, however this does not fully explain the mechanism at work when compressive testing DT fibres.

Table 2 - Compressive strength results

Reference	**Plain concrete P**	**DT 20**	**DT.10 A.**	**DT.10 B.**
1	60.5	58.9	54.1	56.9
2	61.4	61.1	54.9	56.9
3	54.9	56.6	53.8	59.3
Mean	**58.9**	**58.9**	**54.3**	**57.7**
Standard deviation	**3.69**	**2.25**	**0.57**	**1.39**

The plain concrete and the DT 20 concrete had the highest compressive strength and the strength of DT 10. B was not significantly different, when standard deviation is considered, however a very small reduction of 7.7% (DT.10 A) was observed when compared to the plain concrete. This variation is within normal batching tolerances. The DT10A concrete did have the greatest number of fibres per kg added, thus creating more fibre discontinuities which may explain the lower compressive strength.

4.2 Flexural strength

The beams were tested for flexural strength in accordance with BS 12390-5:2000 [25]. All of the samples were weighed and tested in a saturated state. Table 2 displays dimensions, density and flexural strength. The plain concrete had the highest flexural strength and the fibre concrete displayed lower flexural strength values. This was expected due to the introduction of a lower modulus material into the concrete matrix. Beam reinforcement will reduce the area of concrete available to resist the force applied. Therefore a reduction in the area available to resist the tensile forces imposed during the flexural test, will consequently reduce the flexural strength recorded. The relative strength reductions based upon the benchmark of the plain concrete beams were -8.3% (DT20), -21.6% (DT 10. A) and -28.8% (DT 10.B). The DT 20 beams displayed the lowest flexural strength reduction, whereas DT 10 A and B had a greater number of fibres for the same unit weight and therefore display the lowest flexural strengths (see Table 3).

Table 3 – Beam data

Sample Reference	Length mm	Width mm	Height mm	Mass kg	Density kg/m³	First crack load kN	Flexural strength N/mm²
P1f	500	101.8	101.8	11.745	2267	14.87	6.3
P2f	500	100.5	106.5	11.984	2239	16.21	6.4
P3f	500	103.3	100.1	12.288	2377	12.57	5.5
P4f	500	102	101.5	11.818	2283	12.59	5.4
P5f	500	102.1	101.9	11.689	2247	14.37	6.1
P6f	500	101.7	101.4	11.797	2288	14.87	6.4
Mean					**2283**	**14.25**	**6.0**
DT 20.1f	503	103.1	100.2	11.684	2249	13.51	5.9
DT 20.2f	503	106.5	100.3	12.333	2295	13.42	5.6
DT 20.3f	500	101.3	100.3	11.391	2242	9.20	4.1
DT 20.4f	500	101.6	100.7	11.289	2207	12.84	5.6
DT 20.5f	500	101.1	100.6	11.509	2263	13.50	5.9
DT 20.6f	500	100.7	100.3	11.446	2266	13.12	5.9
Mean					**2254**	**12.60**	**5.5**
DT 10.A.1f	500	103.1	100.1	11.31	2192	10.77	4.7
DT 10.A.2f	500	100.8	100.1	11.334	2247	10.66	4.7
DT 10.A.3f	500	100.7	100.2	11.371	2254	10.69	4.8
DT 10.A.4f	500	102.8	101.5	11.912	2283	12.43	5.3
DT 10.A.5f	500	100.3	100.1	11.499	2291	10.55	4.7
DT 10.A.6f	500	102.4	101.7	11.466	2202	9.23	3.9
Mean					**2245**	**10.72**	**4.7**
DT 10.B.1f	500	103.5	101.3	11.467	2187	8.67	3.7
DT 10.B.2f	500	100.4	100.3	11.355	2255	10.01	4.5
DT 10.B.3f	500	101.5	100.5	11.527	2260	10.26	4.5
DT 10.B.4f	500	104.3	103.6	12.12	2243	10.81	4.3
DT 10.B.5f	500	101.7	100.5	11.367	2224	11.19	4.9
DT 10.B.6f	500	104.2	101.2	11.668	2213	8.89	3.7
Mean					**2231**	**9.97**	**4.27**

The plain (elastic – brittle) beams had zero residual strength following the initial crack and the DT 20 and DT 10 B (elastic – plastic) beams displayed strain softening following the initial cracking of the concrete. The DT 10.A beams displayed strain hardening characteristics following the initial crack as displayed in Figure 8. The DT 20 beams showed signs of strain softening immediately after the initial cracking of the concrete, then the dove tailed fibre effect can be seen which was indicated by a rise in the load transfer for an average extension of 0.3mm, thereafter acting as a non linear hinge. The fibres gradually de-bonded and failure, by pull out, was observed in the tension zone below the neutral axis.

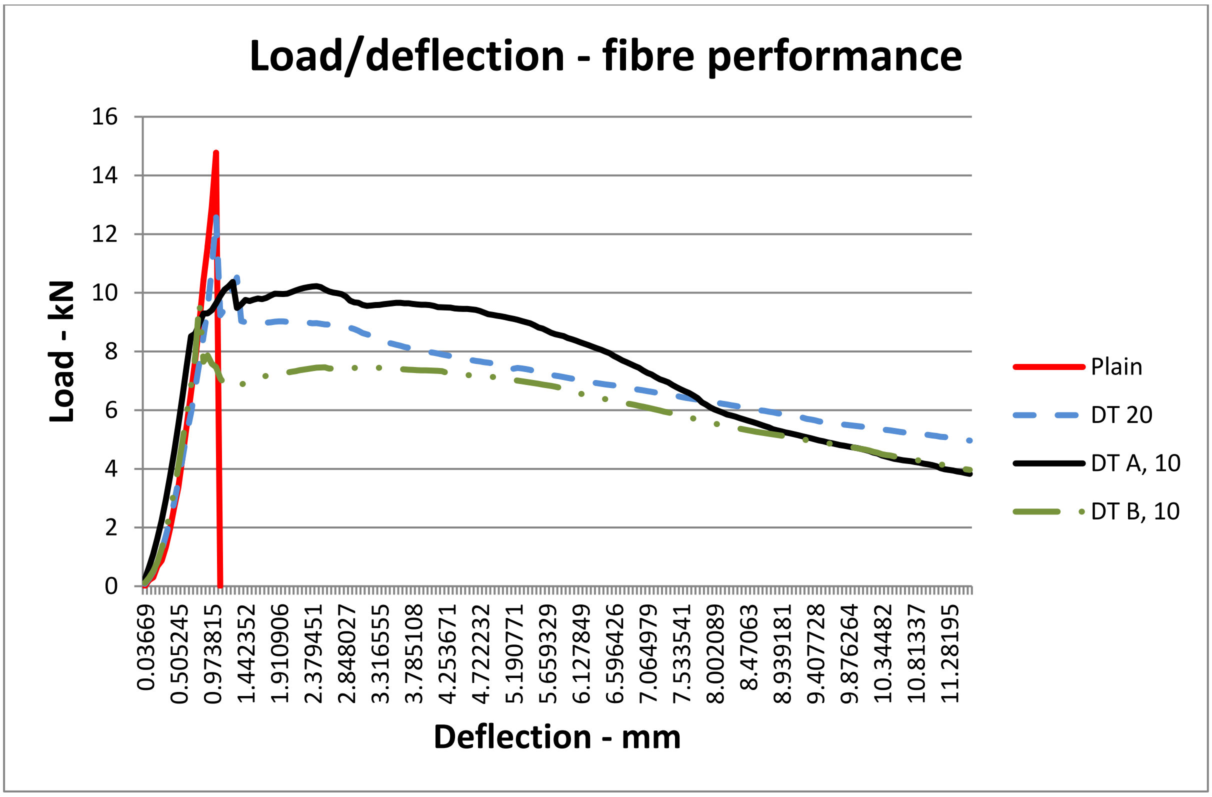

Figure 8 – Load deflection performance

4.3 Toughness

The $CMOD_j$ values are units of flexural strength given as N/mm^2. To achieve a satisfactory performance in accordance with BS 14651, CMOD 1 must be either 1.5 N/mm^2 or above and CMOD 4 must achieve a minimum value of 1 N/mm^2. All of the fibre concrete results exceed the minimum values laid down in the BS for fibre concrete as displayed in Table 4.

Table 4 – CMOD data

Beam ref	Flexural strength at CMOD 1 (CMOD 0.5mm)	Flexural strength at CMOD 2 (CMOD 1.5mm)	Flexural strength at CMOD 3 (CMOD 2.5mm)	Flexural strength at CMOD 4 (CMOD 3.5mm)	Fibres spanning rupture plane
P1f	0	0	0	0	0
P2f	0	0	0	0	0
P3f	0	0	0	0	0
P4f	0	0	0	0	0
P5f	0	0	0	0	0
P6f	0	0	0	0	0
Mean					
DT 20.1F	2.57	2.61	2.48	2.34	39
DT 20.2f	4.38	4.19	4.00	3.78	55
DT 20.3f	4.10	3.81	3.17	2.95	52
DT 20.4f	5.94	5.93	5.77	5.54	74
DT 20.5f	4.47	4.34	4.10	3.84	46
DT 20.6f	3.69	3.67	3.64	3.33	48
Mean	**4.19**	**4.09**	**3.86**	**3.63**	**52**
DT 10.A.1f	5.49	5.09	5.31	5.37	90
DT 10.A.2f	4.62	5.27	5.20	5.19	104
DT 10.A.3f	5.18	5.44	4.86	4.79	95
DT 10.A.4f	5.36	5.10	4.16	3.82	83
DT 10.A.5f	2.82	3.01	3.31	3.48	77
DT 10.A.6f	2.67	3.14	3.44	3.64	58
Mean	**4.36**	**4.51**	**4.38**	**4.38**	**85**
DT 10.B.1f	1.96	2.03	1.97	1.97	58
DT 10.B.2f	3.13	3.44	3.21	3.02	46
DT 10.B.3f	2.00	2.18	2.24	2.07	78
DT 10.B.4f	3.24	3.29	3.40	3.42	69
DT 10.B.5f	3.39	3.66	3.77	3.82	88
DT 10.B.6f	3.73	4.08	4.13	4.01	84
Mean	**2.91**	**3.11**	**3.12**	**3.05**	**71**

The fibres spanning the rupture plane transmit the frictional interfacial post crack forces. The greatest number of fibres equate to the highest post crack load transfer as displayed with the DT10A fibres. The load transfer is dependant upon the angle of the fibre bridging the rupture plane [3], [30]. However it was not practical to determine each individual fibre angle as the breaking force distorted the final fibre angle. The mean values of CMOD 1,2 ,3 and 4 are plotted in Figure 9. The mixed fibre concrete DT 10A outperforms the other batches.

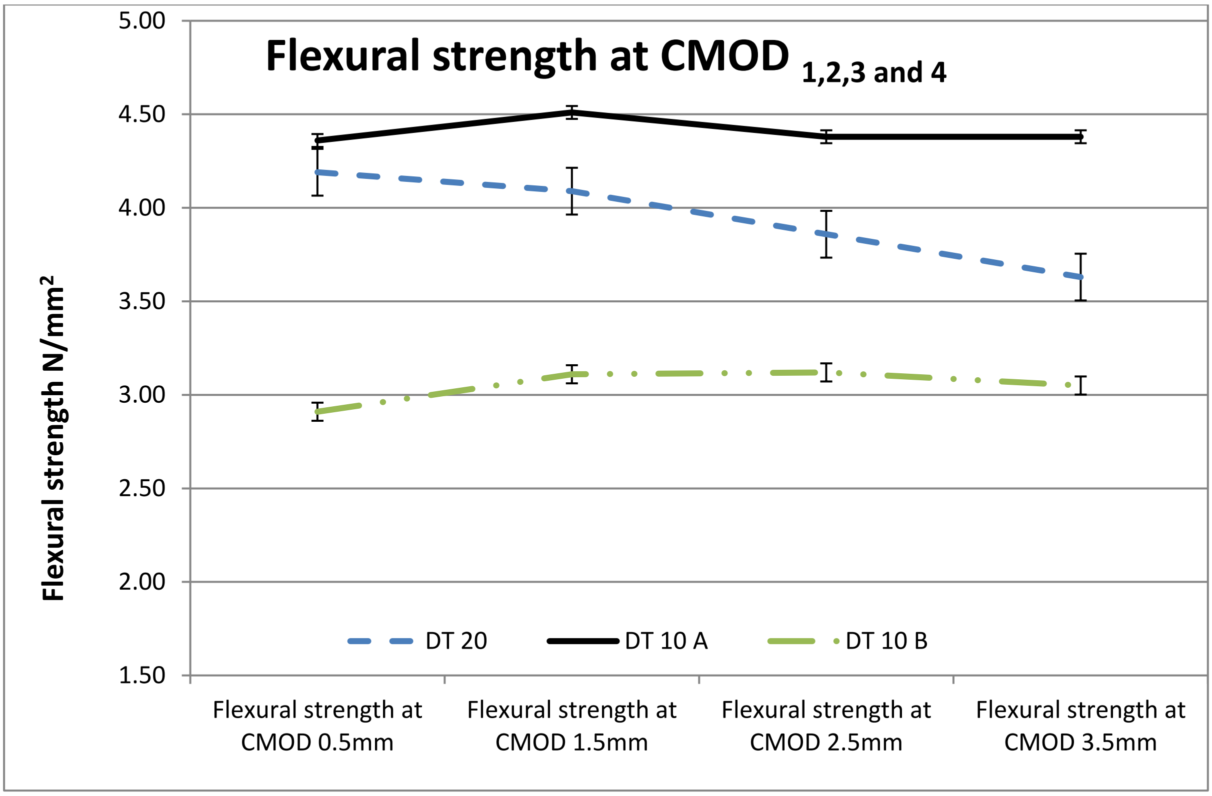

Figure 9 – CMOD flexural strength values.

The test was terminated at around eleven times the deflection from the initial crack, informed by ASTM 1018. All of the DT 20 beams were still capable of transferring post crack forces. Examination of the fibres spanning the rupture plane showed pull out (ductile failure) was the main mode of failure, however on observation a small proportion of the "A" fibre type failed due to brittle fibre fracture. The marine sandstone gravel aggregate failure was mainly due to shear.

The performance of the dovetailed fibres provided a very even flexural strength between CMOD 1 and 4. When this is compared to Type 2 synthetic fibres tested to the same British standard [5] the different is notable in that the non DT synthetic fibres displayed a marked reduction in flexural strength between CMOD 1 and 4.

4.4 Impact data

The impact testing was carried out using an Instron CEAST drop hammer apparatus. A pilot test was undertaken to establish the optimum drop height and tup weight. Plain unreinforced beams sheared fully at 150mm drop with a 5 kg weight added to the tup creating a total mass of 10.032 kg and the beams had no residual structural capability as shown in Figures 10 and 11.

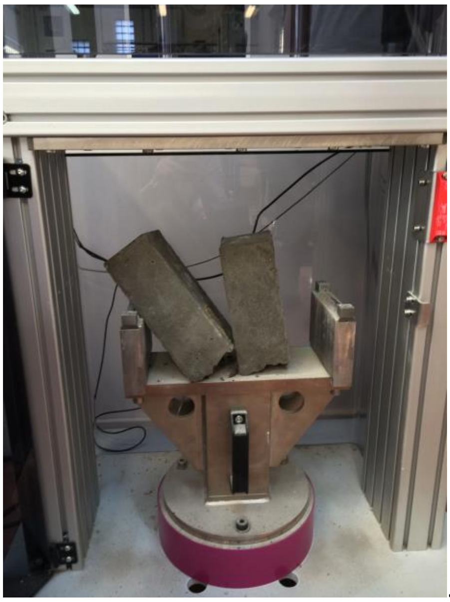

Figure 10 – Plain beam following impact.

Figure 11 – Fractured plain beam

Figure 11 displays the failure mode of the beam, and this was sheared aggregate and cured cement paste, with minor aggregate pull out failure being visible.

Final drop hammer velocity was calculated using Equation 1

$$m\,g\,h = \frac{1}{2} m\,\mathbf{u}^2 \qquad [1]$$

Where

m = Mass of the drop hammer (kg)

g = gravity (9.81 m/s^2)

h = height of the drop (m)

$\mathbf{u}$ = final velocity of approach (m/s)

Kinetic energy absorbed by the specimen was calculated using Equation 2.

$$E_t = \frac{1}{2} m \mathbf{u}^2 \qquad [2]$$

Where

E_t = Kinetic energy

The impact velocity for the plain concrete beams was 1.72 m/s and the impact energy at this rate of descent was 12.913 J. An observation to note was that, the same test arrangement did result in any cracking of the fibre reinforced beams. The beams fully absorbed the impact without any visible damage. Consequently the drop height was increased by 50 mm for the fibre reinforced beams to create a small crack width, in the region of 0.3mm to 0.55mm as displayed in Figure 12.

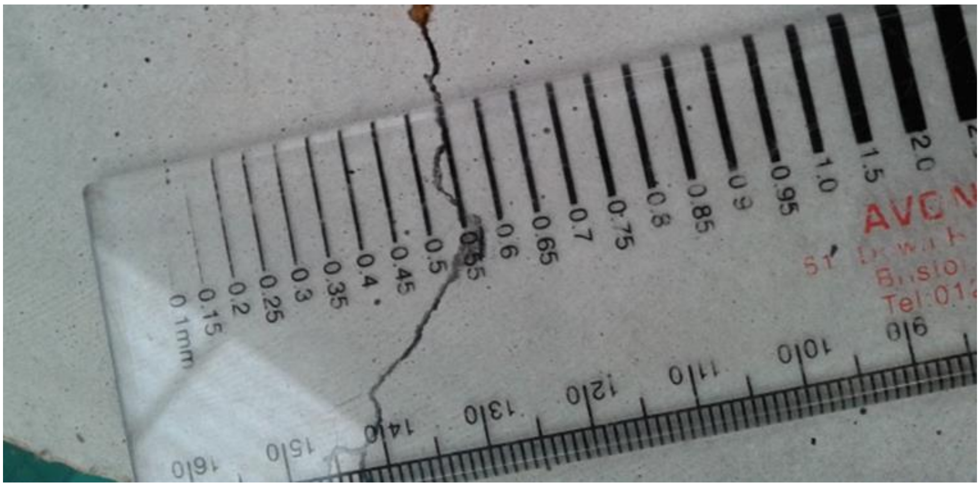

Figure 12 – crack width on fibre beam

The minimum crack width measured is normally used to define the maximum serviceability limit state design and for the purpose of this test was deemed to be satisfactory. The impact velocity for the fibre beams was 1.98 m/s and the impact energy at this rate of descent was 17.130 J. The results from the impact test are displayed in Table 5.

Table 5 – Beam and Impact data

Beam ref	Length mm	Width mm	Height mm	Mass grams	Density kg/m^3	Peak Force N	Total Impact Energy Joules
P1i	425	101.4	102.3	10.125	2297	21013	6.512
P2i	424	100.2	100.6	9.933	2324	21942	12.877
P3i	425	101.3	101.1	10.225	2349	25394	11.122
P4i	424	101	100.5	10.11	2349	30388	11.53
P5i	424	100.8	100.4	10.072	2347	38144	12.608
P6i	425	99.8	100.6	10.061	2358	20199	6.404
Mean					**2337**	**26180**	**10.176**
DT 20.1i	425	97.1	100.3	9.753	2356	38380	18.832
DT 20.2i	425	102.3	101.6	10.032	2271	37228	16.931
DT 20.3i	425	101.8	100.8	9.872	2264	38387	16.618
DT 20.4i	425	99.5	100.8	9.782	2295	38174	16.671
DT 20.5i	421	100.4	101	9.656	2262	38384	16.684
DT 20.6i	425	103.4	100.8	9.973	2251	38417	20.145
Mean					**2283**	**38162**	**17.647**
DT 10.A.1i	425	100.6	100	9.91	2318	45101	16.547
DT 10.A.2i	424	100.9	100.3	9.774	2278	39547	16.483
DT 10.A.3i	423	101.3	100.2	9.947	2317	46987	16.104
DT 10.A.4i	424	100.3	100.2	9.964	2338	48124	16.791
DT 10.A.5i	423	101.4	100.1	9.963	2320	56523	16.599
DT 10.A.6i	424	100.8	100.4	9.883	2303	42729	16.485
Mean					**2312**	**46502**	**16.502**
DT 10.B.1i	425	101.7	101.2	10.007	2288	27963	9.793
DT 10.B.2i	425	101.9	100.9	9.96	2279	38389	17.054
DT 10.B.3i	421	102.3	103.3	10.139	2279	28089	12.787
DT 10.B.4i	425	104.1	100.8	10.02	2247	38157	16.655
DT 10.B.5i	425	102.6	100.8	9.836	2238	36656	16.652
DT 10.B.6i	423	100.6	101.1	9.742	2264	28344	13.640
Mean					**2266**	**32933**	**14.430**

Comparing the density of the different concrete mixes against the plain mix, DT 20, DT 10A and DT 10B were less dense respectively by 2.3%, 1.1% and 3.0%. This would be expected when comparing the relative densities of concrete (2307 kg/m^3) and polypropylene (900 - 950kg/m^3). The plain and DT 10A concrete density is above the nominal value for normal concrete of 2307 kg/m^3 as shown in BS 648 [31] and the DT 20 and DT 10B are below this value. The variation in densities would not be expected to influence the impact results.

Using the plain beams as a benchmark, there was improved performance with the use of fibres in beams. The increase in peak force was 45.8% (DT 20), 77.6% (DT10A), and 25.8% (DT 10B) and the increase in total impact energy was 73.4% (DT 20), 62.2% (DT 10A), and 41.8% (DT 10B). The DT 20 beams re-distributed the highest impact energy.

The average impact force and deformation is displayed in Figure 13.

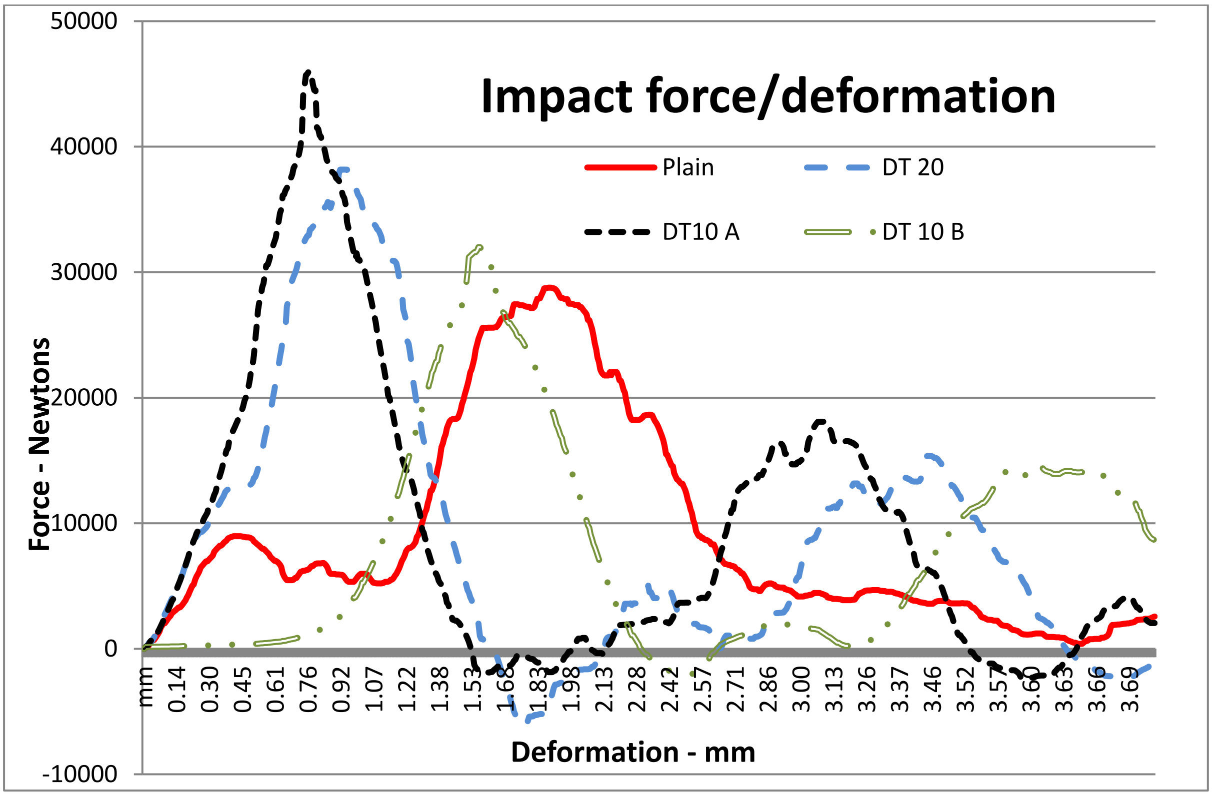

Figure 13 –Average impact data (Force/deformation)

Table 6 displays the average time in milli seconds between the initial impact, the initial break point and the total failure of the beam.

Table 6 – Impact, break point and total break times

Beam	Average time (milli seconds) between start and break point	Average time (milli seconds) between start and total failure	Percentage change compared to plain concrete between start and break point	Percentage change compared to plain concrete between start and total failure
Plain	0.572	0.581	0	0
DT 20	0.736	1.839	29%	317%
DT 10 A	0.630	1.834	10%	316%
DT 10 B	0.738	1.952	29%	336%

Figure 14 displays the initial, break and final break positions for plain and fibre beam impact comparison. The fibre beams hold together under impact for a longer duration than the plain concrete beams.

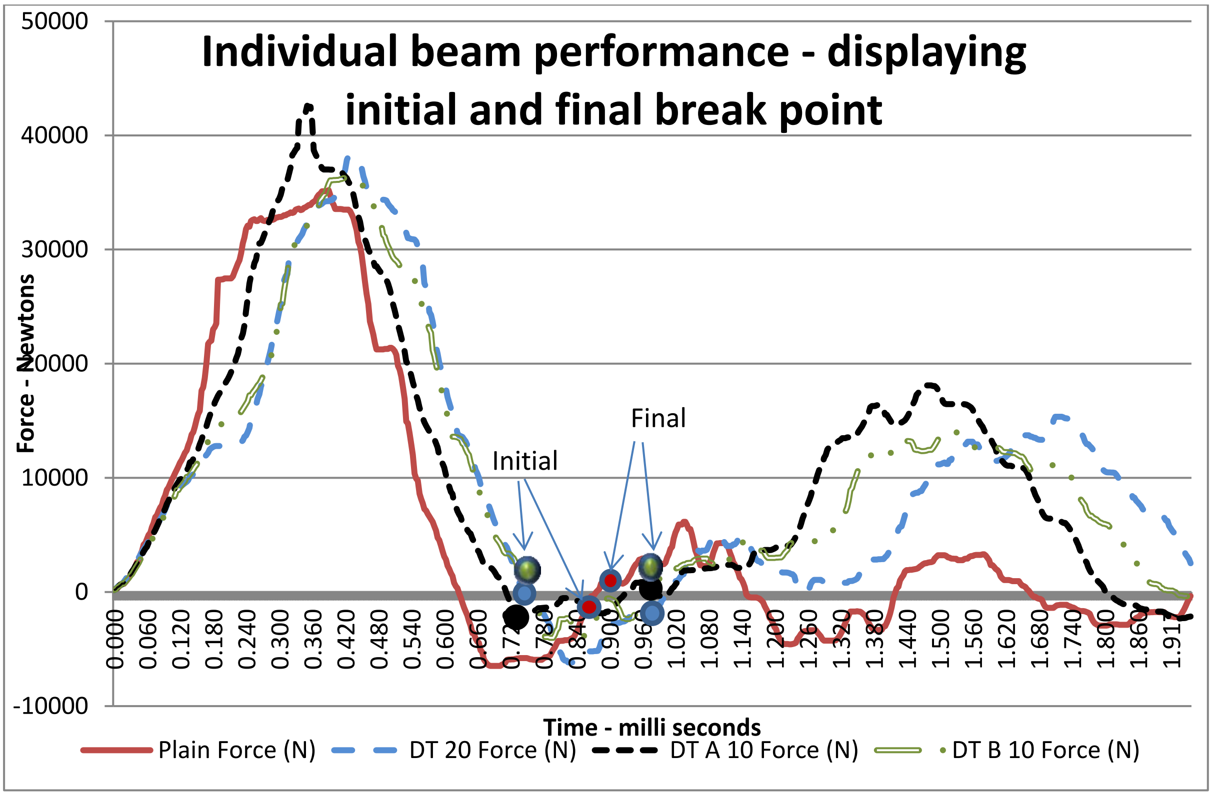

Figure 14 – Individual beam performance – displaying initial and final break point.

The fibre beams held together as a lightly cracked unit following the initial impact and were capable of absorbing further impacts before ultimate limit state was achieved.

4.5 Rifle fire ballistic testing

The air temperature on the day of the test was 18°C which provided an air density value of 1.2125 kg/m^3 with regard to deceleration of the bullet. This temperature is neutral in terms of bond strength between the fibres and the concrete matrix. High temperatures can weaken the bond strength due to a dissimilar expansion co-efficient. Each slab received a single shot centrally without any observable variation to the test procedure.

Post shot observation of the slabs, found all slabs to be penetrated through their full thickness. Fragments of disintegrated bullet casing were found in the aperture made by the bullet. Fibres were embedded into the timber wall behind the firing range.

The plain samples produced fragments of concrete flying back towards the source of the bullet for a distance of 20m as displayed in Figure 15. This was thought to be due to the brisance effect of the shock wave travelling through the samples and bouncing back off the rear face, as discussed in Section 1.2.

Figure 15 – Concrete fragment (plain)

The brisance effect is generally affected by pressure. The higher the pressure, smaller the fragments.

Measurements of the impact damage to the concrete slabs was recorded to the nearest 5mm, and mean values are shown in Table 7. The most damage observed was within the plain samples and the least damage was within slabs DT A. The depth and diameter of the impact cone was less with the fibre concrete samples; as was the penetration hole diameter.

Table 7 – Ballistic observations

Concrete ref	Impact hole at surface (mm dia)	Impact hole at centre (mm dia)	Impact hole at exit (mm dia)	Depth to centre of hole from front face
Plain (P)	117.5	26	100	35
DT 20	85	21	75	15
DT 10.A	75	18	80	12
DT 10.B	85	20	85	12
% change (P) to A	57	44	25	191

The plain sample (P) broke into 4 and 2 pieces respectively and suffered many hair line fractures as displayed in Figure 15.

Figure 15 – Post test, plain sample with least damage

Type DT 10B fibre samples outperformed the other fibre samples and the sample is displayed in Figure 16. There were fine hairline cracks present after the impact but they did not go through the thickness or perimeter of the sample.

Figure 16 – Sample B.

Less concrete was ejected back towards the source of the projectile with all fibre samples.

5.0 Conclusion

The hybrid DT10A mix displayed the only strain hardened result with regard to the load/deflection transfer mechanism and the peak impact load was significantly higher than the other fibres as tested. In addition the DT 10A fibre beams displayed the lowest impact to break point, but similar impact to final failure to the other fibre beams. A lower impact to break point value was due to the superior bond strength of the hybrid fibres as displayed in Figures 7 and 8 and this created a quasi brittle material.

The hybrid DT10A mix was only marginally outperformed on the impact energy results by the DT 20 beams and this was due to the DT 20 concrete's ability to absorb large degrees of strain. The CMOD performance of DT10A was significantly better than the other fibre beams and this level of load transfer at CMOD 4 showed no loss of strength from the initial crack at CMOD 1.

The ballistic tests showed a distinct improvement in impact resistance between plain and fibre concrete with the hybrid type DT 10A mix suffering least damage.

All of the synthetic fibre results are similar in performance, however the DT fibre technology can be seen to be in operation, by examination of Figure 7 when comparing the beams, this fibre type has the best ability to re-distribute the impact forces in a beam once de-bonding has occurred. The DT fibre has a use in structural engineering design where resilience, ductility, high degrees of strain and impact energy absorption is required.

Further work

The test should be repeated with 100% smaller diameter DT fibres and this would better equate the number of fibres available for force transfer to match the best performing DT 10 A concrete. Smaller fibres equate to a greater surface area per kilogram available to resist the forces across the rupture plane and more ends to fray and provide post crack bond.

A further test is needed to evaluate the concrete performance when the load is increased, such as large projectile or blast tests. The two concrete types in need of testing are the DT 20 with smaller diameter fibres and the hybrid DT10 A concrete, that also uses smaller diameter fibres. These tests would complete the performance profile of the concrete and provide a real life situation against which the energy absorption could be measured.

References

[1] Hsie M, Chijen Tu, and Song P S, (2008), Mechanical Properties of Polypropylene Hybrid Fibre Reinforced Concrete, *Materials Science and Engineering A, 4*94, pp 153 – 157

[2] Richardson A, Coventry K A, and Boussoffara R, (2013), Performance of dove tailed synthetic fibres in concrete, *Emerging Materials Research*, ICE, DOI:10.1680/emr.13.00040

[3] Bentur A and Mindness S, (2007), *Fibre Reinforced Cement Composites*, 2nd Edition, London: Taylor And Francis.

[4] Richardson A.E., Coventry K., and Landless S., (2010) Synthetic and steel fibres in concrete with regard to equal toughness, *Structural Survey*, Vol. 28 Iss: 5, Emerald Group Publishing Limited, pp.355 - 369

[5] Richardson A E and Jackson P, (2011), Equating steel and synthetic fibre concrete post crack performance, 2nd International Conference on Current Trends in Technology, NUiCONE, December 8 – 10, Nirma University, Ahmedabad, India

[6] Destrée, X. (2007), Structural Steel-fibre-Reinforced concrete construction, *Concrete,* Vol. 41 no. 8, pp. 23-24

[7] Bentur A, Peled A, and Yankelevsky D, (1997), Enhanced Bonding of Low Modulus Polymer Fibres-Cement Matrix by means of Crimped Geometry, *National Building Research Institute*, Technion-Israel Institute of Technology, Haifa 32000, Israel, p1099.

[8] Parviz S and Cha-Don Lee, (1990), Distribution and Orientation of Fibres in Steel Fibre Reinforced Concrete*, ACI*, pp 433 - 439

[9] Richardson A E, (2007), *A comparative study of post crack flexural toughness with A142 fabric steel reinforcement and structural polypropylene fibres in medium strength concrete beams*, International Conference on "Advances in cement based materials and applications in civil infrastructure – (ACBM – ACI)", Lahore Pakistan, December 12 – 14.

[10] Millard, S.G., Molyneaux, T., Barnett, S. and Gao, X., (2009), Dynamic enhancement of blast-resistant ultra high performance fibre-reinforced concrete under flexural and shear loading, *Department of Engineering, University of Liverpool,* Elsevier Ltd.

[11] McVay, M.K. (1988), Spall damage of concrete structures, *department of the Army US Corp of Engineers*, US Army, p.1 – 23.

[12] Mays G.C. and Smith P.D., (1995), *Blast Effects On Buildings*, 2nd Ed, London: Thomas Telford, p.2

[13] Elsayed, N.M. and Atkins, J.L., (2008). Explosion and blast-related injuries effects of explosion and blast from military operations and acts of terrorism. *Burlington,* Elsevier p.46

[14] Gutierrez de Ceballos., (2005), The terrorist bomb explosions in Madrid, Spain - an analysis of the logistics, injuries sustained and clinical management of casualties treated at the closest hospital, *Critical care*, Vol. 9 issue 1 p.107

[15] Hibbert A P and Hannant D J, (1981), Impact Resistance of Fibre Concrete, TRRL Supplementary Report 654, Transport and Road Research Laboratory, *Department of the Environment*, UK pp 1 - 24

[16] Betterman L R, Ouyang C, and Shah S P, (1995), "Fiber-Matrix Interaction in Microfiber-Reinforced Mortar"*, Advanced Cement Based Materials*, Elsevier, pp 53 – 61.

[17] British Standards Institution (2007) BS EN 14845-1, *Test Method for fibres in concrete – Part 1: Reference Concretes,* BSI

[18] British Standards Institution, BS EN 197-1:(2000), Cement — Part 1: Composition, specifications and conformity criteria for common cements

[19] British Standards Institution BS EN 1008:2002, Mixing water for concrete —Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete

[20] British Standard Institution (2006) BS EN 14889-2: 2006, *Fibres for concrete- Part 1: Steel Fibres – Definitions, specifications and conformity,* BSI

[21] Thomas W M, Thomas R L, Paglia C, Ralph B, and Fenn R, (2011), Evaluation of novel fibre reinforcement by punch testing, *Concrete,* June, Vol 45, Issue 6, UK

[22] British Standards Institute, (2009), BS EN 12390-3:, Testing hardened concrete. Compressive strength of test specimens London: British Standards Institute

[23] Richardson A E, (2006), Compressive Strength of Concrete with Polypropylene Fibre Additions, *Structural Survey*, Vol 24, No 2, August, MCB UP Ltd, UK, pp 138 – 153.

[24] Martin G, (2012), The case for Structural Synthetic Fibres, *Concrete,* May, Vol 46, Issue 5, The Concrete Society, UK

[25] British Standards Institute, (2000), *BS 12390-5:2000, Testing Hardened Concrete – Part 5- Flexural Strength of Test Specimens*, London: British Standards Institute

[26] Vellore S, Golpalaratham V.S.and Gettu R, (1995), On the Characteristics of flexural toughness in fibre reinforced concrete, *Cement and Concrete Composites*, Vol 17, Issue 3, pp 239-254

[27] ASTM, American Society for Testing Materials, (1997), *C 1018, Standard test method for flexural toughness and first crack strength of fibre reinforced concrete*, USA: ASTM.

[28] British Standards Institution (2005) BS EN 14651:2005+A1: 2007, *Test Method for metallic fibre concrete – Measuring the flexural tensile strength (Limit of Proportionality (LOP) residual),* BSI

[29] Millard, S.G., Molyneaux, T., Barnett, S. And Gao, X., (2009), Dynamic enhancement of blast-resistant ultra-high performance fibre reinforced concrete under flexural and shear loading, *International Journal of Impact Engineering,* Vol 37, Issue 4, Elsevier Ltd, pp 405 - 413

[30] Hannant D J, (1998), The effects of age up to 18 years under various exposure conditions on the tensile properties of a polypropylene fibre reinforced cement composites, Vol. 32 pp 83 – 88, *Rilem*, 1359-5997/99

[31] British Standards Institution, BS 648, (1964), *Schedule of Weights of Building materials*