RECENT DEVELOPMENTS IN FRC TECHNOLOGY FOR ENHANCED IMPACT RESISTANCE PROPERTIES: INNOVATIONS AND OPPORTUNITIES

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ABSTRACT. To defend against extreme accidental and intentional loadings, a need for developing civilian and military structures having high impact resistance and ductility has been realized. Present endeavour aimed at reviewing latest innovations on functionally graded fiber reinforced concrete (FRC) composites in past three years for improved impact resistance under both slow velocity and high velocity impact regimes. The processing technique of FRC slabs for impact testing with volume fraction of reinforcement used was noted. Based on recently reported studies in archival literature on FRC composites, it was understood that ultra-high performance concrete (UHPC) reinforced with steel fibers being tested at 550 m/s ∼ 800 m/s, polyamide (PA) bundle type fiber reinforced with plain concrete (PAFRC) being tested at 296m/s ∼421m/s and short polypropylene fiber reinforced concrete (PPFRC) being tested at 190m/s ∼ 420m/s exhibited superior impact resistance than conventional FRC during high velocity projectile impact testing. Similarly for low impact velocity regime, high strength high ductility concrete (HSHDC) reinforced with polyethylene fiber, polythene terephthalate (PET) reinforced with plain concrete and layered two stage fibrous concrete (LTSFC) slabs depicted improved impact resistance than plain concrete. Modifications in previous fabrication procedures of FRC and introduction of polymeric fibers in concrete instead of convenational FRC has put up a way forward for exploring impact performance of fibrous self-compacting, recycled aggregate, geopolymer rubberized materials etc. in FRC technology.

Keywords: Plain concrete, Fiber reinforced concrete composite, Drop weight collision test, High velocity rigid projectile test, Impact resistance.

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INTRODUCTION

In present situation, the expanding number of worldwide fear based oppression exercises and dynamic loading emerging from seismic tremors has made high impact resistance capability in civil and military foundations essential. This has tempted numerous researchers to revise and improve upon existing fiber reinforced concrete materials [1-3]. Laboratory impact testing consists of two types of arrangements i.e. drop weight collision test for slow velocity impact and projectile velocity test for high velocity impact. Local damage during velocity impact can be characterized into three modes i.e., (a) Spalling (b) Scabbing and (c) Perforation, depending upon the impact resistance of FRC and velocity of impact as shown in Figure 1.

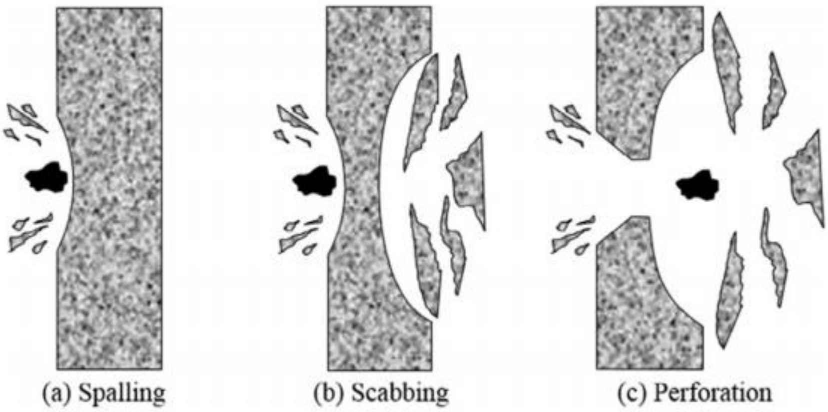

Figure 1 Modes of local damage on concrete plate

Spalling refers to spewing of target material from closed face of the target plate. Scabbing means ejection of materials into fragments from distal face of target plate whereas perforation causes tunnelling in target plate by projectile path [4]. The spalling depth is measured as distance in between deepest dent and impact face. Crater diameter caused by scabbing and spalling is determined by measurements taken along four directions from the centre of impact. Although, numerous combination of steel fibers and polymeric fibers have been attempted by various researchers in the past to study their influence on high and slow velocity impact resistance of FRC. To limit the scope of current review, recent developments on FRC technology from year 2010 were reviewed in detail and are presented in chronological order in Table 1.

Table 1 Studies on impact behaviour of FRC from 2010 in chronological order

Authors	Aggregates and binding material	Fiber type with percentage	Impact test parameters	Key findings
Nili and Afrough-sabet,	Coarse and fine aggregates; Cement and	Hooked end steel fiber (0.5% and 1%	Drop weight impact test: 4.45kg	• Impact resistance increased with steel fiber and silica

2010 [5]	silica fume 30.8 and 36.0 kg/ m^3 (replaced cement)	by volume fraction)	hammer dropped repeatedly from a 45.7cm height onto a 6.35cm steel ball	fume. • Results depicted that incorporation of silica fume as a pozzolan material and steel fiber as an arrestor of crack propagation considerably improved the ability of concrete to absorb kinetic energy.
Nili and Afroughsabet, 2010 [6]	Coarse and fine aggregates; Cement and silica fume 30.8 and 36.0 kg/ m^3(replaced cement)	Polypropylene fibers (by volume fractions of 0%, 0.2%, 0.3% and 0.5%)	Drop weight impact test: 4.45kg hammer dropped repeatedly from a 45.7cm height onto a 6.35cm steel ball	• Addition of silica fume in fibrous specimens made them more impact resistant i.e. number of blows. • Addition of silica fume facilitated the dispersion of fibers and improved the strength properties, particularly the impact resistance of concretes.
Farnam et al., 2010 [7]	Cement, Sand, Metakaolin and superspelizer Polycarboxylate	Steel fiber (by volume fraction of 2 %)	Drop weight impact test: Low velocity - 4.23 m/s	• High performance fiber reinforced cement based composite (HPFRC) had higher impact resistance than plain concrete. • Addition of steel fibers to plain concrete made it more impact resistant.
Nyström And Gylltoft, 2011 [8]	Plain concrete	Steel fiber	Numerical simulation	• At <1% fiber percentage, a negligible decrease of projectile penetration depth compared to plain concrete was observed. This would lead

				to reduced crack propagation beyond the crater region, so that damage is confined to a more localised volume. • At >1% fiber percentage, relatively small change of the front face crater was evaluated. Therefore, it reduced crack propagation beyond the crater region.
Alavi Nia et al., 2012 [9]	Concrete matrix with cement binder	Hooked end steel fiber (by volume fraction of 0.5 % and 1%), polypropylene (PP) fiber (by volume fraction of 0.2%, 0.3% and 0.5%)	Drop weight impact test: 4.45 kg weight dropped repeatedly from a 457mm height onto a 64 mm steel ball	• Impact strength of hooked end steel fibers was better than polypropylene fibers reinforced concrete. • This was because of their larger length, greater tensile strength and better cohesion due to their hooked-ends.
Aliabdo et al., 2013 [10]	Pink limestone, Basalt and sand, Cement binding material	PP fiber (by volume fraction of 0.1%, 0.2 %), Steel fiber (by volume fraction of 1.0% and 2.0 %), Waved steel fiber (by volume fraction of 1% and 2%), Hooked end steel fiber (by volume fraction of 1% and 2%)	Drop weight impact test: Cylindrical steel mass weighing 33kg dropped from a height of 610mm	• Steel fibers were more effective than propylene fibers, type of coarse aggregate has negligible effect, and steel fiber volume fraction had more significant influence than firer shape for reinforced concrete test panels.

				• The presence of steel fibers had a significant effect on penetration depth, entrance crater area and crack width.
Almusallam et al., 2013 [11]	Fine sand, silica sand, Cement, normal concrete and high strength concrete	Plastic fiber (by volume fraction from 0.2% to 0.9%) and steel fiber (by volume fraction from 0.2% to 0.9 %)	High velocity projectile impact test: Hardened steel projectile of mass 0.8kg and 40mm in diameter projected with different velocity up to 300 m/s.	• Test results showed that the hybrid-fibers in the concrete led to smaller crater volumes and reduced the spalling and scabbing damage. • The hybrid-fibers arrested the crack development and thus minimized the size of the damaged area.
Máca et al., 2014 [12]	Cement, Silica fume, Glass powder silica and fine sand	Steel fiber (by volume fraction of 1% ,2% and 3%)	High velocity projectile impact test: Weight of the projectile 8.04grams and average muzzle velocity 710m/s (Two types of projectile i.e. deformable and non deformable).	• Specimens containing 2% of fibers by volume had optimal resistance against deformable projectile impact. • In case of ultra high performance FRC slabs the crater diameter decreased by 42% to 50% compared to conventional FRC specimens.
Dancygier et al., 2014 [13]	High strength concrete, Dolomite aggregate, Single and double layered	Steel fiber (by volume fraction 0 Kg/m^3, 60 Kg/m^3 and 80 Kg/m^3)	High velocity projectile impact test: Weight of the projectile	• For plain (non-fibrous) concrete, better perforation resistance was obtained in two

	fiber reinforced specimens		1750grams and average muzzle velocity 300m/s	layer specimens compared to single-layer. • Barriers with a thicker front layers and large aggregates exhibited increased perforation resistance, irrespective of the use of fibers. The addition of fibers, however, enhanced overall performance.
Wu et al., 2015 [14]	Ultra-high performance cement (UHPC), Basalt coarse aggregates, Silica fume, Fly ash.	Steel fiber (by volume fraction from 0% to 4%)	High velocity projectile impact test: 510m/s–1320 m/s	• Experiments validated that UHPCC material had excellent resistance, such as reducing the depth of penetration and the crater dimensions of the rigid projectile, as well as defeating the structure and deviating the terminal ballistic trajectory of the abrasive projectile.

LATEST STUDIES ON LOW VELOCITY IMPACT RESISTANCE BEHAVIOUR OF FRC

High strength high ductility concrete (HSHDC) is a newly developed polyethylene fiber reinforced cementitious composite with a combination of tensile ductility (>3%) and compressive strength (>150 MPa). Ranade et al., 2017 compared impact load resistance of HSHDC thin slabs (300mm × 300mm × 25mm) reinforced with steel fibers with ultra high performance concrete (UHPC). A constant weight of 16.04kg was dropped repeatedly on both HSHDC and UHPC slabs using a cylindrical steel head of 75mm diameter from three different heights of 0.35 m, 0.70 m, and 1.40 m in a drop weight impact test set – up as shown in Figure 2(a). Under multiple drop-weight impacts, while HSHDC slabs maintained their impact load-bearing capacity up to 20 impacts and structural integrity as shown in Figure 2(c), UHPC slabs gradually lost their capacity and failed before the 20th impact. On increasing the impact velocity caused more rapid reduction of impact resistance of UHPC slabs with the number of impacts as shown in Figure 2(b), whereas, it has negligible effect on the behaviour of HSHDC slabs, which exhibited almost minimum reduction in impact strength with the number of impacts at all velocities investigated in this study [15].

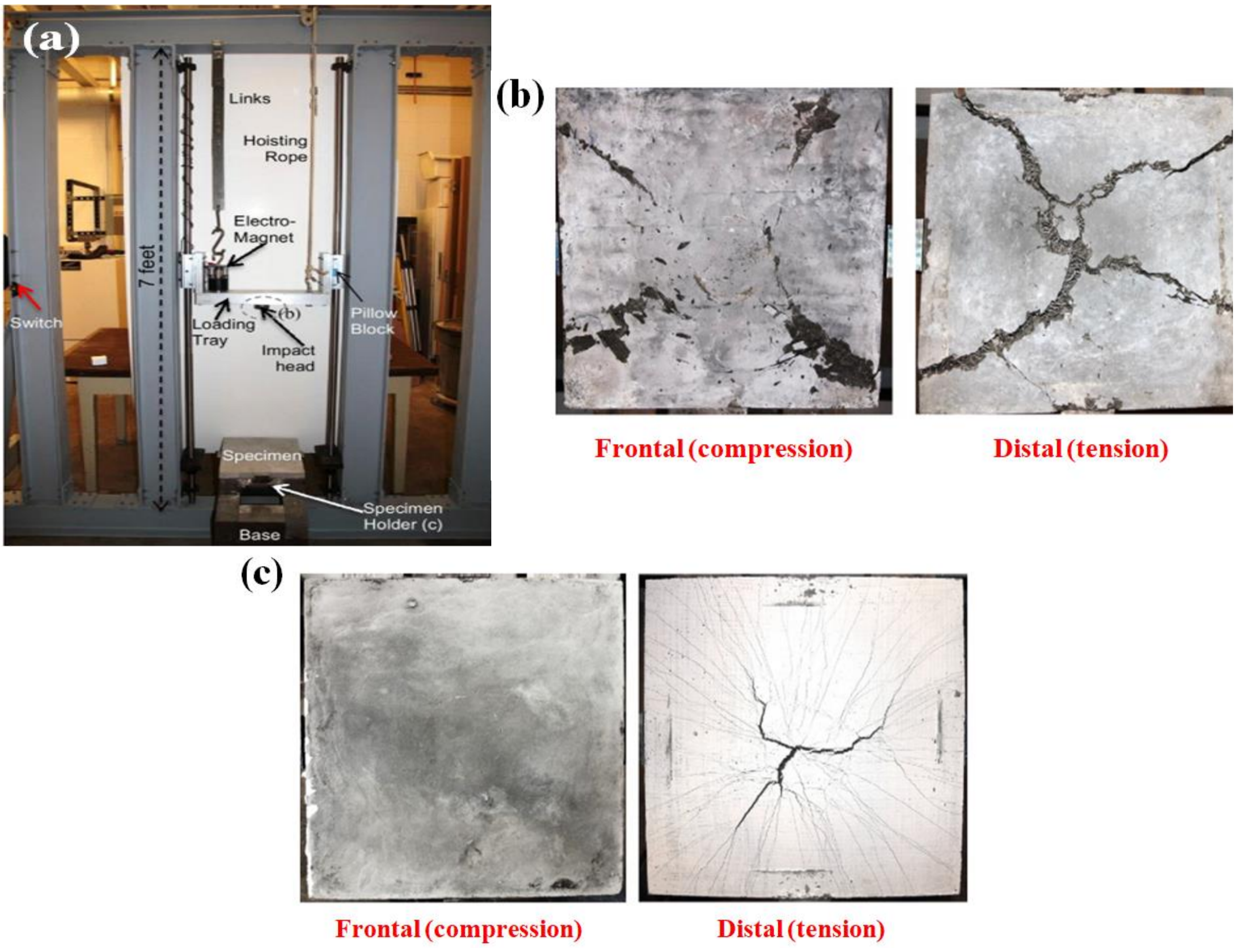

Figure 2 (a) Drop-weight impact test setup (b) Damage condition of UHPC slab after 19 impacts (c) Damage condition of the HSHDC slab after 20 impacts [15]

Disposed of plastic items after culmination of their required service life have prompted an enormous collection of solid waste in almost every developing country [16-18]. Saxena et al., 2018 used waste of polythene terephthalate (PET) in chopped form as a replacement to coarse and fine aggregates in concrete to study the impact resistance behaviour [19]. Weight percent fraction of PET varied was 5%, 10%, 15% and 20% in the PET-concrete mixture. 4.5kg cast iron ball was dropped from 450mm height on specimens of 150mm diameter and 75mm thickness in drop weight test equipment as shown in Figure 3(a). Number of blows up to initiation of first crack denoted as N_1 and up to failure denoted as N_2 increased with increasing PET aggregate replaced fine and course aggregate which was due to improved ductile behaviour of specimen as shown in Figure 3(b) and Figure 3(c).

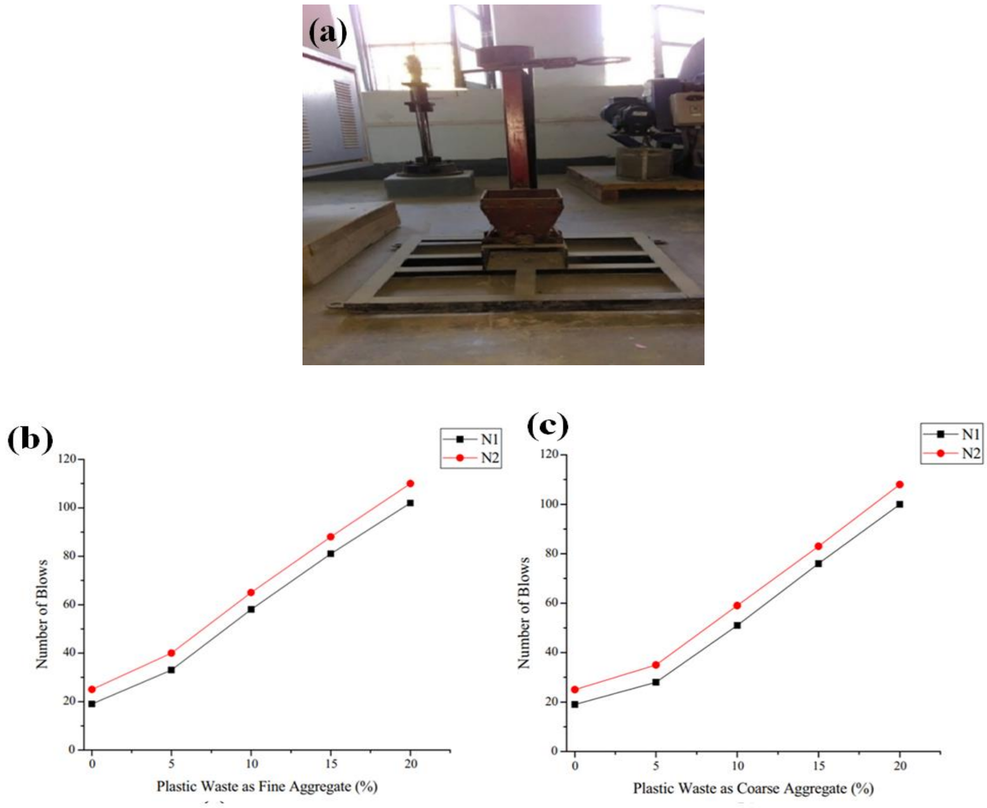

Figure 3 (a) Drop weight apparatus (b) Number of blows for fine aggregate (c) Number of blows for coarse aggregate [19]

Murali and Ramprasad, 2018 developed novel layered two stage fibrous concrete (LTSFC) whose impact strength was compared with conventional two stage fibrous concrete (TSFC). LTSFC specimens were prepared with three layers of coarse aggregates and a combination of steel fibers in contrast to a single layer for TSFC specimen as depicted in Figure 4(a) and Figure 4(b). Falling weight collision testing set up is shown in Figure 4(c). Results reveals that LTSFC exhibited an impact crack resistance ratio greater than 1, which depicted the great ductility as regards to entirely reinforced concrete with equal fiber content (TSFC) [2]

LATEST STUDIES ON HIGH VELOCITY IMPACT RESISTANCE BEHAVIOUR OF FRC

Kim et al., 2015 developed polyamide (PA) bundle type fiber which was different from commonly used fibers like polyproelene, steel, armid etc. PA bundle type fiber having 544μm diameter were entangled and looped into a bundle with final diameter of 0.5 mm by air injection technique. The study endeavoured to compare high velocity impact resistance of PA bundle type fiber reinforced concrete, hooked end steel fiber reinforced concrete and plain concrete (without fiber). Figure 5(a) and Figure 5(b) show enlarged view of steel and PA fiber exhibiting morphological differences. It is pertinent to mention here that loop obtained from PA fiber has enhanced fiber/matrix bond strength which is attributable to less elongation of individual PA fiber. To improve the flowability of PA fiber in concrete, they were coated with hydrophilic and lipophilic reagents as depicted in Figure 5(c). Impact testing was conducted with a steel projectile ball of 10mm diameter at impact velocity of

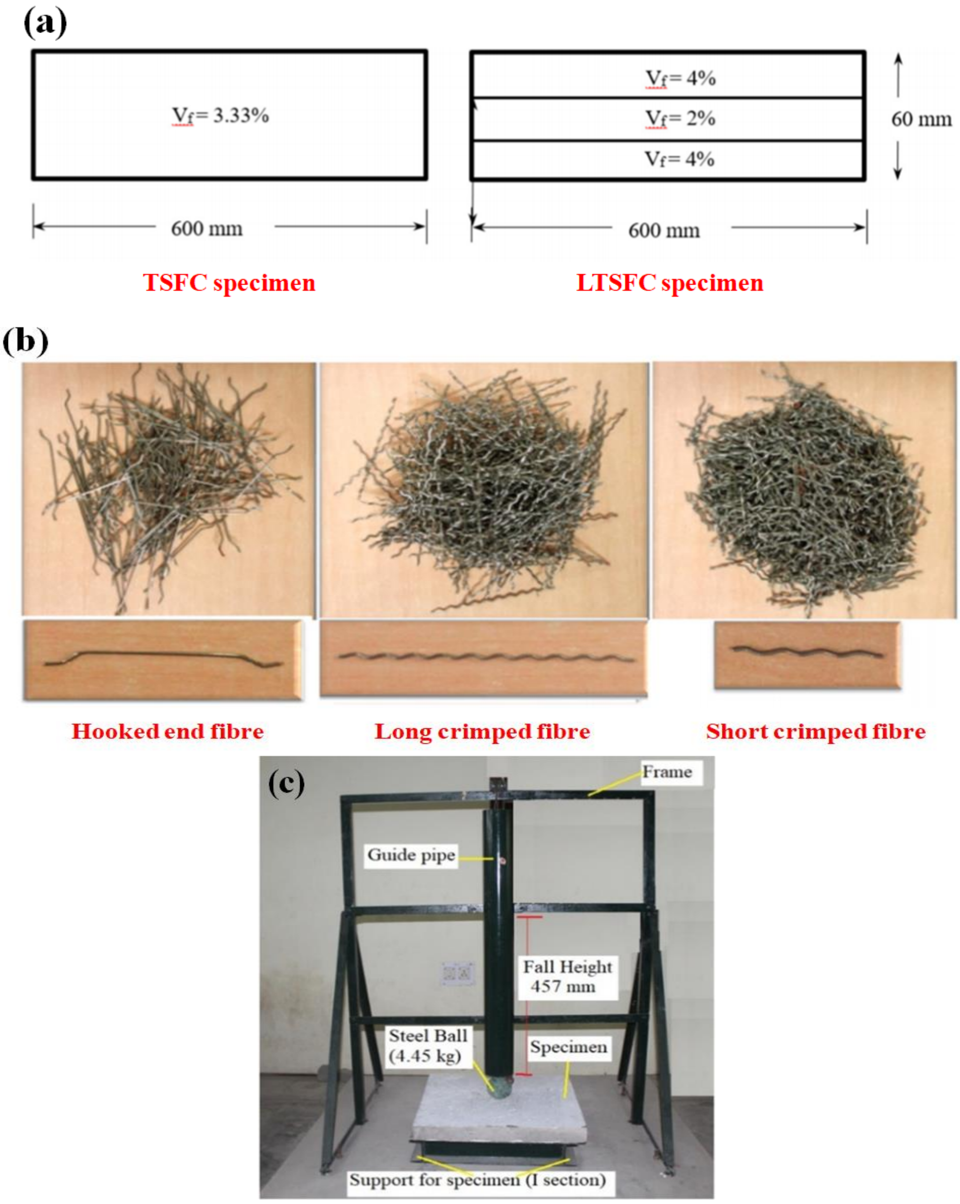

Figure 4 (a) TSFC and LTSFC specimens (b) Geometry of fibers (c) Falling weight collision testing set up [2]

300m/s. Appearance of diagonal cracking led to scabbing. Intense shock waves produced inside the plain concrete plate were a primary cause of local failure in plain concrete as observed in Figure 5(d). Whereas low number and uneven distribution of hooked end steel fibers resulted in wider crack formation which led to failure through scabbing and pulling out of hooked end fibers from the matrix as depicted in Figure 5(e). However, increased number and uniform distribution of PA fibers in matrix imparted improved impact resistance and resulted in fiber breakage with narrow cracks. This signified that shock wave absorbing energy of concrete was remarkably increased upon increasing the fiber density in the matrix [20].

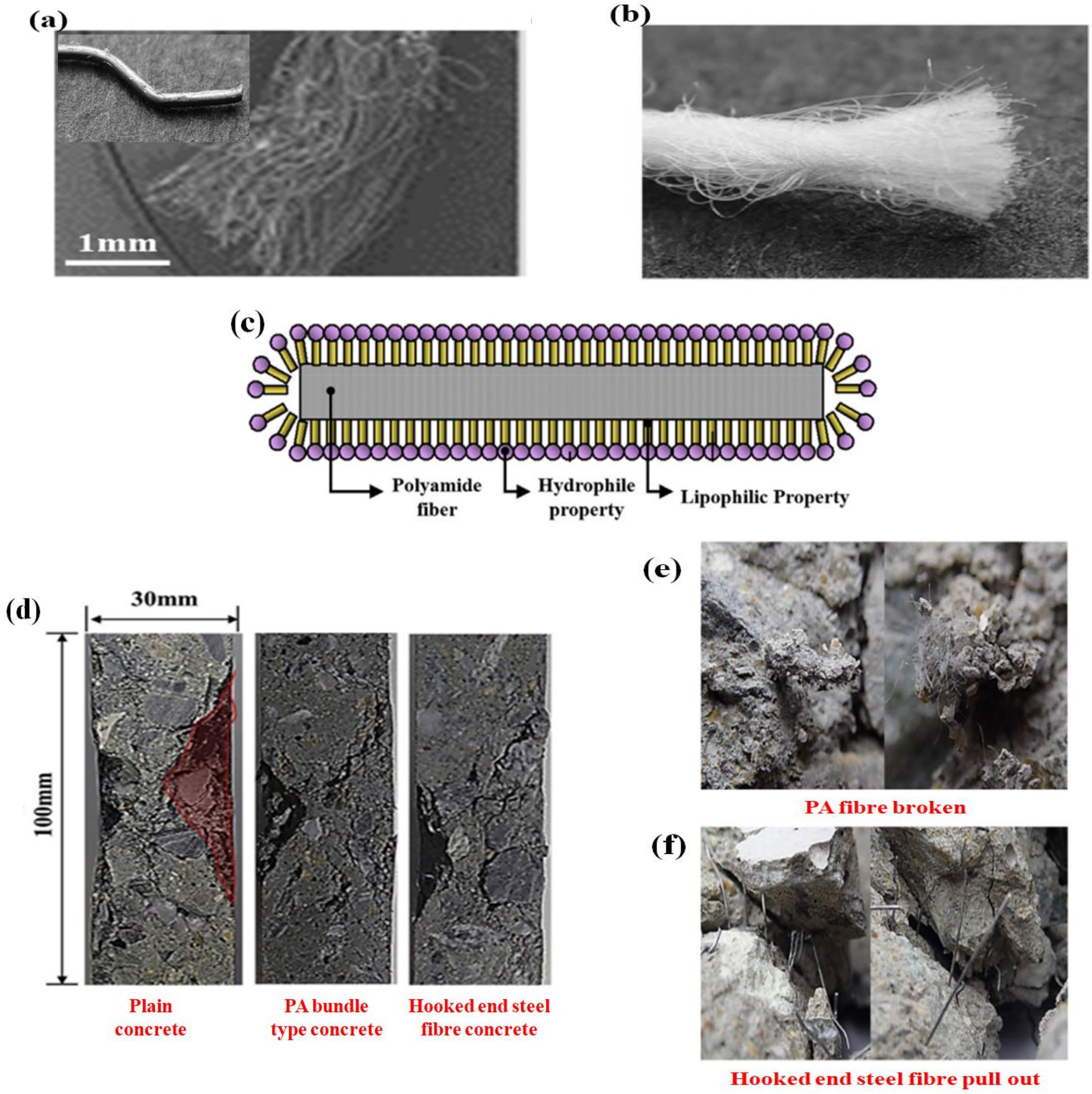

Figure 5 (a) Hooked end steel fiber (b) PA fiber (c) PA surface coating (d) Local damage at 300 m/s with 10mm diameter projectile (e) Fiber pull out and broken fibers after impact test [20]

Ueno et al., 2017 compared short polypropylene fiber reinforced concrete (PPFRC) plates with plain concrete being subjected to high velocity projectile impact by steel ball of 46grams mass. As regards to other fibers of steel, armid, polyvinyl alcohol, the polypropylene fiber had improved deformability. Projectile velocity was varied from 190m/s to 420m/s on 80mm thick plates. The projectile launching set up and steel projectile with nylon sabot is shown in Figure 6(a) and Figure 6(b). Scabbing and perforation were observed at 296m/s and 421m/s impact velocities respectively in plain concrete as shown in Figure 6(c). However failure modes in PPFRC at impact velocities of 298m/s and 415m/s were spalling and scabbing respectively as observed in Figure 6(d) which indicated a significant increase in impact resistance of PPFRC. It was inferred from these findings local failure at high impact velocity was suppressed in PPFRC as a result of its high energy absorption owed to the bridging effect of the short polypropylene fibers [21].

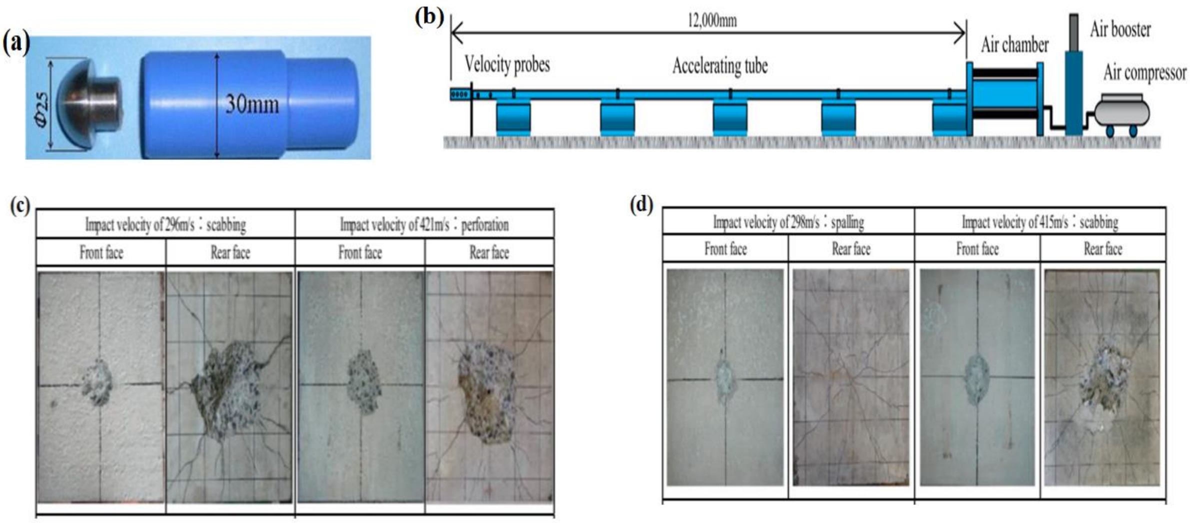

Figure 6 (a) Steel projectile and nylon sabot (b) Set up for projectile launch (c) Plain concrete (d) PPFRC [21]

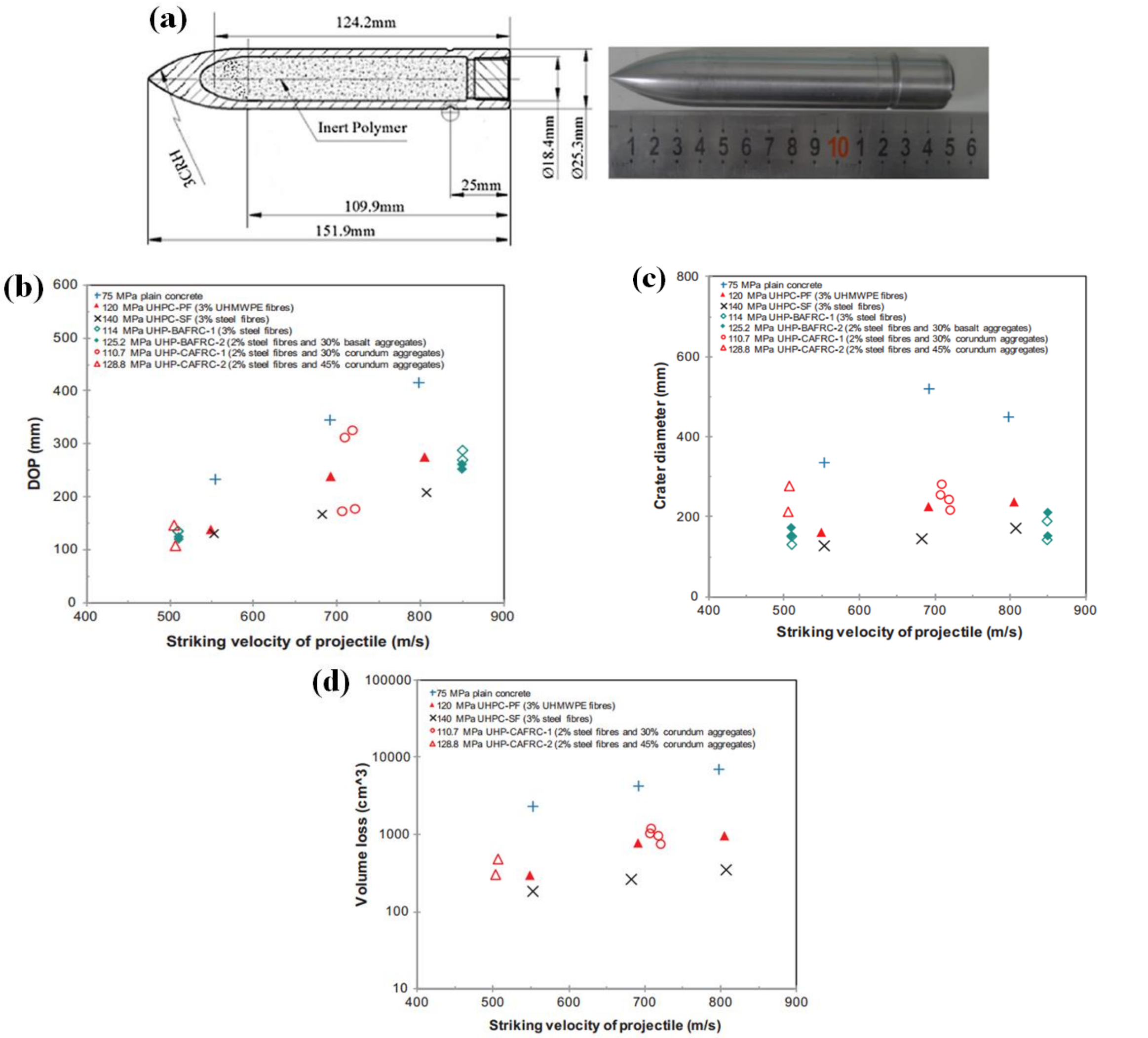

Figure 7 (a) Ogive nosed projectile (b) DOP versus striking velocity of projectile (c) Crater diameter versus striking velocity of projectile (d) Volume loss versus striking velocity of projectile [22]

Liu et al., 2018 compared impact behaviour of plain concrete (PC), ultra-high performance concrete (UHPC) reinforced with steel fiber (UHPC-SF) and ultra-high molecular weight polyethylene (UHMWPE) fiber (UHPC-PF) at 3% volume fraction each. Parameters investigated were depth of penetration (DOP), crater diameter and volume loss at high velocity i.e. ~550 m/s, ~675 m/s and ~800 m/s. Ogive nosed projectile as shown in Figure 7 (a) was used for this purpose. Samples in cylindrical shape of PC, UHPC-PF and UHPC-SF were prepared having 700 mm thickness and 750 mm diameter. It was found that DOP, crater diameter and volume loss of UHPC-PF and UHPC-SF was much smaller than that of PC. These parameters increased with increase in impact velocity at ~550 m/s, ~675 m/s and ~800 m/s of impact velocity. The percentage reduction in DOP of UHPC-SF compared to UHPC-PF was 7.9%, 30.5% and 24.1% at these impact velocities. Results obtained from this experimentation are collated in Figure 7(b-d). Improved impact resistance of UHPC-PF and UHPC-SF than PF was attributed to the bridging effect of fibers [22].

CONCLUDING REMARKS

From a short review of the literature particularly on newly developed processing methods of fiber reinforced concrete and introduction of new type of fibers in them for obtaining improved impact properties, the following conclusions have been drawn:

Global terrorism activities and dynamic loading has become a significant problem for in-service FRC composites. Laboratory results on plain concrete and steel FRC by slow and high velocity impact testing have shown poor impact resistance in contrast to polyethylene reinforced high strength high ductility concrete, polythene terephthalate (PET) concrete composite, polyamide fiber bundle type concrete composite etc. Considerable improvements in impact properties of conventional FRC has stemmed from recent innovations like coating of polymer fibers, increasing the fiber density in concrete matrix and using waste like PET.

Usage of polymer as major portion in concrete matrix, the slow and high velocity impact performance of fibrous self-compacting, recycled aggregate and geopolymer rubberized are some of the unexplored possibilities. In this respect, effect of hydrophilic and lipopilhic coating on these types of fibers on overall impact performance of concrete slabs should also be investigated.

Current review also focused on technological aspects which are of useful interest in the fabrication of FRC technology for civil and defence structures, particularly in fiber material engineering. However, to improve the deep understanding on different reinforcing fibers influencing the impact properties, detailed research into the atomic processes at the interface during fiber/matrix bonding is still necessary.

The widespread employment of FRC solely depends upon the rejuvenation of existing methods and techniques. Modification of existing FRC fabrication methods requires extensive multi-disciplinary efforts to achieve better impact properties.

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