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# A REVIEW OF HYBRIDISED USE OF FIBRES IN SHEAR BEHAVIOUR OF FIBRE-REINFORCED CONCRETE BEAMS

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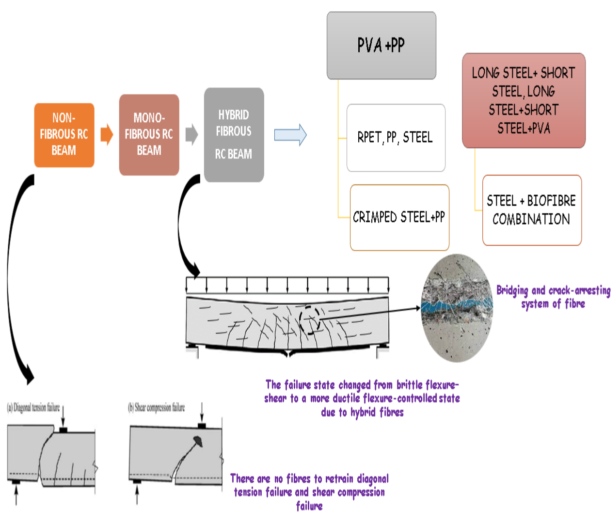
**Graphical abstract**




**Abstract**

Shear failure of the concrete beam is always disastrous due to unnoticed occurrences and is avoided in construction. Introducing fibres into concrete elements has provided significant shear support to reinforced concrete beam structures through stress redistribution after initial cracking and bridging mechanisms. Given their advantages over single fibre strengthening in past years, using hybrid fibres in an optimal combination as strengthening in cementitious materials has drawn much interest. However, research on this area remains inexhaustible based on the emerging various fibre combinations and the challenge of unnoticed concrete shear failure. Therefore, reviewed research articles on shear performances of Fibre Reinforced Concrete (FRC) beams considering the effect of fibre volume, lengths and orientation on the synergy. The findings reveal the possibility of synergising fibre to enhance reinforced concrete beam(RCB) shear performance for metallic-metallic, metallic-synthetic, synthetic-synthetic, and metallic-biofibre combinations, with varying performance. Using low-strength/modulus fibre with high strength has been effective for shear resistance. Also, beam type (deep/shallow), fibre type and volume fractions, length, aspect ratio, orientation and distribution remarkably affect the shear performance of RC beams.

*Keywords*: Beam shear failure, Fibre characteristics, Fibre hybridisation, Fibre-reinforced concrete beam, Shear performance



## 1.0 INTRODUCTION

The increasing demand for high-performance concrete for complex structures necessitates the incorporation of short and discrete fibres into concrete to improve tensile strength, toughness, impact resistance and crack restrictions. Numerous civil engineering projects have extensively used fibre-reinforced concrete (FRC), including machine footings, shotcrete, and hydraulic and reinforced structures [1]. FRC was developed by combining the concrete matrix with short and discrete fibre, improving toughness and post-cracking tensile strength because of the fibre-bridging system [2]. Also, beams function to receive a load from the slab and transfer it to the column, as shear stresses in Reinforced Concrete (RC) beams are taken care of by placing stirrups. Deep beams perform differently from slender beams due to the internal shear-resisting mechanisms and comparatively minimal shear-to-span-depth ratio. Thus, shear controls deep beams as flexure controls slender beam systems [2]. However, the aversion of RC beams to shear resistance is one of the current stimulating research discourses. This is because specific parameters affect reinforced concrete beams' shear actions, so modelling such becomes difficult due to their dynamism [3]. This becomes more complex of how shear force interacts with other loads such as; torsional, flexure and axial load. The collapse of RC beams due to flexures is often preferred to collapse due to shear that does not give prior warning, making this review essential.

The role of fibres in the shear strength of RC beams has been well-established in the literature. Self-consolidating concrete [2], conventional concrete [4], high-performance [5,6], and UHPFRC [7] have been studied. Shear strength of 9% to 37% was observed in RC beams with fibres, such that the fibres prohibited shear failure, changing the collapse mechanism from shear to flexure [8]. Based on studies, steel fibres can be viewed as a shear reinforcement that substantially impacts concrete structures' ultimate shear capacity and ductile nature. Based on [9,10], report steel fibres may totally or partially replace conventional shear reinforcements, depending on the type, proportion and concrete strength grade. This includes [11] that steel fibre can partially replace the shear reinforcement. It is quite essential to know that fibres can not replace longitudinal steels and stirrups in beam shear functions. However, fibre plays a remarkable role in mitigating RC beam shear failure, following the development of the initial diagonal crack, fibres regulate crack outreach and permit unprecedented interior plastic stress redeployment to boost the specimens' shear strength.

Besides, one of the pioneering researchers on FRC beams (Al-Ta'an and Al-Feel [12] studied the decisive shear strength of FRC beams, where 89 beams were loaded to shear failure. It was concluded that, apart from the significant reinforcing bar proportion and compressive strength, the span-to-depth fraction of the shear and fibre volume, type, and dimensions are critical to the shear behaviour of the FRC beam. Shape, fibre aspect ratio (l/d) and fibre volume affect how effective RC beams respond to loading. Even after cracks appear, fibres added to concrete remain functional and withstand tension until they yield. While fibres retain a random distribution of crack arrest, typical reinforcement stops cracks at specific places. Also, how each fibre performs in shear differs. For example, steel and polypropylene fibres act differently in shear because of the difference in their materials' elasticity modulus. The difference is evident in stirrup stresses, which are lower for steel fibre-reinforced concrete than for a polypropylene fibre-reinforced beam.

Researchers have applied single fibre to study shear performance in RC beams. Single fibre application in RC beams has been reported to mitigate shear failures [2–5,7,13–17]. However, fibre performances in RC beams are often limited by the single use of fibres whose strain and crack openings are efficiently restricted, such that the single fibre can enhance the strength or ductility of the composite [16]. Concrete, being a complicated material, the structure comprises numerous phases. A micron-scale calcium-silicate-hydrate gel and millimetre and centimetre-scale fine/coarse aggregate make up the concrete structure, respectively. It is impossible to expect gains in all phases when employing only one type of fibre in a concrete system, including complex stages. Instead of employing a single fibre, FRC developed using different fibre types with various forms and dimensional features will have greater technical benefits and more useful capabilities [18]. Thus, the focus has shifted to synergistic and optimal utilisation of fibres beneficial in enhancing RC beam property and beam shear resistance [19,20].

The idea of a hybrid is the merging of two or more fibres in a cementitious composite to counter the cracking progressions of concrete under various loading phases, to harness each fibre's properties based on various types, geometry, and shape, in a combined functionality for improved performance. Also, to achieve toughness and ductility, fibres of high modulus with poor flexibility and fibres of low modulus with high flexibility must be merged [21]. High-modulus fibres are; steel, glass, and carbon, while low-modulus are; nylon and polypropylene. Thus, combining fibres of varying mechanical characteristics is essential to achieve a concrete composite with strength and pliability enhancement. Many parameters could affect the shear performance of RC beams, like; compressive strength, the proportion of flexural steel, shear span-to-depth ratio, element height and fibre characteristics. Many literature review articles have been reported on these parameters [22–25], except for fibre characteristics and geometry. Besides, quite some studies have been conducted on RC beam property improvement through fibre hybridisation [22,26–28]. However, research on this area remains inexhaustible based on the emerging various fibre combinations and the challenge of unnoticed concrete shear failure. Fibre characteristics could vary with intended usage. However, fibre types and features used in this review are presented in Figure 1 and Table 1, respectively. The fibre categories are; metallic, synthetic, and natural, and they are; Steel, Polypropylene (PP), Polyvinyl Alcohol (PVA), Recycled polyethene Terephthalate (RPET), Cellulose, Kenaf and Basalt fibres. Materials for this review were obtained from the reputable Scopus and Google Scholar research databases.

This paper brings to the forefront the current knowledge on the synergistic (hybridisation) use of fibre (metallic, synthetic, and natural) for effective RC beam shear performance based on experimental studies, considering the criticality of beam shear failure and the upsurge in fibre application in FRC structures lately. The review paper contains a shear-resisting system of FRC beam, the fibre hybridisation idea, and its impact on beam shear performance for various fibre combinations. This paper would serve as helpful guidance on the synergetic use of fibres for RC beam shear improvement.


**Figure 1:** Some Common Fibres Used in RCB [29–34]

## 2.0 SHEAR RESISTING SYSTEM IN FRC BEAM

The development of a single crack rules plain concrete failure. Before the initial crack forms, the material displays linear elastic behaviour. A crack develops when the maximum primary tensile stress surpasses the concrete's tensile strength, causing a collapse of localised material. The direction of the most significant primary tensile stress acting on the material is normal to the crack's plane [4]. Cracking propagates with increased load; fibre inclusion provides a crack-curbing/bridging mechanism, and fibres stop the crack openings after crack initiation [35,36].

Various possible failure scenarios exist depending on how well the fibres bridge cracks. As a result, fibres could help increase concrete sections' bending and shear strength by preventing cracks from spreading under flexural and shear-induced diagonal tension [4]. Navarro-gregori et al. [37] reported that fibre shear efficacy was determined by reinforcing bars across the shear plane. Marar et al. [16] reported that the moment the aggregate interlock mechanism becomes less effective as the crack width widens and can transfer shear forces over small cracks. The strength of the concrete, the width of the fissures, the volume of coarse aggregate, and the mechanical qualities of mortar all affect the shear transfer abilities across the fractures. Diagonal fractures develop and spread when the critical tensile stresses in the shear domain of a reinforced concrete beam surpass the tensile strength of concrete, which causes an abrupt beam failure [38]. Adding fibres to concrete transforms the behaviour from brittle to ductile, causing an enormous ultimate strain in FRC than in plain concrete; fibres' primary purpose is to prevent fractures' formation and growth [3,39,40]. Following the development of cracks in FRC, the primary energy-dissipating processes are fibre-matrix interface slip-away, fibre fracture, fibre pullout, and fibre shear yielding, depending on the fibre's material characteristics, length, and geometry [39].

In the case of shear cracking, it is essential to know that shearing stress is a crucial part of beam load-bearing capability [41], and the number of crack openings largely influences beam shear disposition [4]. Also, (Karthik and Maruthachalam [42] emphasised the need to understand what determines the diagonal cracking strength of concrete elements, Based on the concept of concrete fracture mechanics. According to studies, three variables working together—unfractured concrete in the compression area, aggregate interlocking, and shear operating across the longitudinal steel bars—resist shear force. Shear force could be described as dowel force when it is applied across steel bars, and this is the concrete's tensile strength connected to its compressive strength when diagonal cracks in concrete are initiated and spread through the beam web [42]. An example of a beam under shear cracking is shown in Figure 2. Also, Figure 3 shows the impact of fibres in absorbing energy as revealed in each stage of matrix cracking, fibre/matrix debonding, bridging, pullout and fibre failure. Fibre helps dissipate energy that would have caused shear failure to flexural failure. Abbas et al. [4] studied the possibility of incorporating steel fibre to lessen the usual quantity of stirrups. The insertion of steel fibres improved the material's ability to carry loads, increased ductility, and changed the collapse mode from brittle shear to flexural ductile.

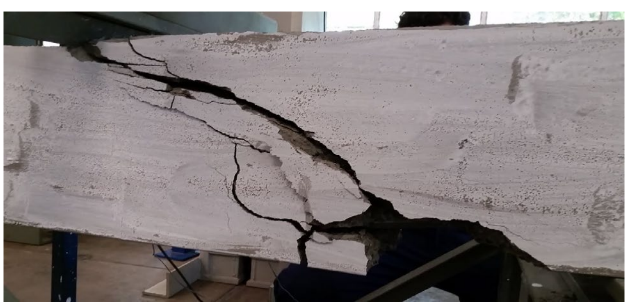


**Figure 2:** Shear Failure of a Reinforced Concrete beam near the prop

**Table 1** Characteristics of Fibre Used in This Review [42–44]

| Fibre type | Length (mm) | Diameters (mm) | Aspect ratio | Tensile Strength (Mpa) | Elastic Modulus (Gpa) |
|---|---|---|---|---|---|
| Steel | 30 | 0.5 | 65, 80 | 1200 | 212 |
| PP | 12 | 0.02 | 300 | 451 | 4.5 |
| PVA | 12 | 0.04 | 300 | 1600 | 39 |
| RPET | 38 | 0.02 | 1900 | 155 | 6-14 |
| Cellulose | 2.3 | 16µm | 155-60 | 300 | 35 |
| Kenaf | 30 | 39.7-115µm | 40-80 | 380 | 18 |
| Basalt | 12 | 0.01 | 230, 530 | 2100 | 79 |

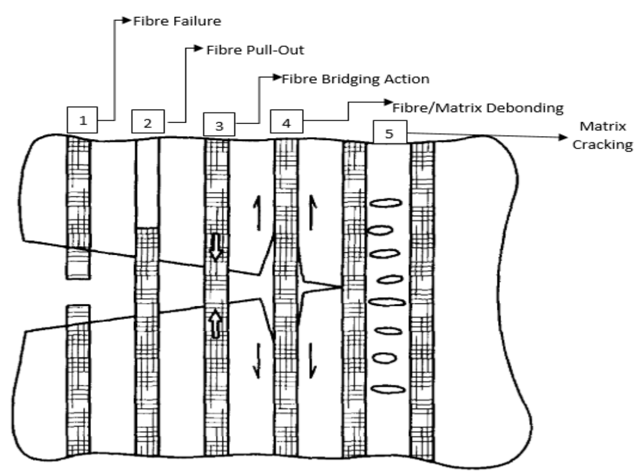



**Figure 3:** Energy-absorbing fibre-matrix systems [45]

## 2.1 Concept of Fibre Hybridisation in RC Beam Shear Performance

The current design standards demand a compact reinforcement arrangement for shear-prone structural members leading to reinforcement jamming that could increase construction time or reduce construction quality. However, combining fibres with various lengths, diameters, moduli, and tensile strengths is a different FRC beam development technique. The idea of a hybrid is to harness each fibre's properties based on various types, geometry, and shape, in a combined functionality for improved performance. Due to the differences in the sizes of the fibres, hybridisation based on fibre length and diameter is advantageous. The fracturing mechanisms of tension-loaded concrete start with producing multiple fine microcracks in the interfacial zones around aggregate particles; if the tensile load is increased further, these microcracks will link and form larger cracks, failing. Based on the concept of concrete fracture mechanics, Markovic [35] studied the diverse usage of short and long fibre steel fibres in concrete beams. Therefore, to estimate the synergistic efficiency of the hybrid mixes, the best fibre orientation was achieved during the casting of the samples. The results indicated that the short fibres increase the tensile strength and the long fibres increase the ductility of Hybrid-Fibre Concrete Figure 4 (a) depicts the impact of squat, thin fibres on microcrack bridging since they are skinny and the amount in concrete is substantially more significant than the amount of long thick fibres given the equivalent fibre volume quantity. Also, because this microcrack occurs in the first stage of tensile loading, short fibres are likely to improve the tensile strength of the beam.

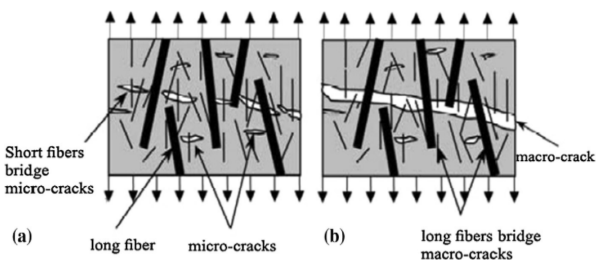



**Figure 4:** (a) Short-fibre effect on microcrack bridging and tensile strength improvement (b) Long-fibre impact on microcrack bridging and ductility enhancement [35].

It may be vital to determine the synergy of different hybrid mixtures to know the efficacy of the hybridisation. [43] discourages adopting typical rule-of-mixtures to envisage the impact of hybridisation on toughness due to uneven fracture mechanisms and the interaction between various fibres within the mixture. Therefore, in other to estimate the synergistic efficiency of the hybrid mixes, a formula was recommended;

$$Synergy = \frac{PCT_{hybrid,a+b}}{PCT_a + PCT_b} - 1 \quad [43] \qquad \text{Eq. 1}$$

Where; PCT stands for the Post Crack Toughness Factor for the different mixtures. Flexure is determined in this situation by adding the flexural toughness factor to a deflection, *d*,($FT_d$), and deducting the flexural toughness factor from the plain concrete mix. The area under the load-deflection plot is used in the event of direct shear similarly, but without considering the matching area connected with non-fibrous concrete. According to this method, a constructive synergy (>0) occurs when a hybrid of fibres creates characteristics that are numerically bigger than the sum of the characteristics created by a single fibre type. Synergy has two possible values: zero means no synergy, while negative means the hybrid performs worse than the sum of its parts.

## 3.0 FIBRE HYBRIDISATION EFFECT ON BEAM SHEAR PERFORMANCE

Much research has been conducted on the synergistic use of fibres in property enhancement [42,43,54,46–53]. However, the types of fibres to be combined are of great importance. In the hybrid reinforcement field, steel-steel and synthetic-synthetic combo do not receive much research attention as steel-synthetic fibre combinations. This is because combining steel fibres, with low-strength, high-density, and synthetic fibres, with low strength and density increase cementitious composites' ductility, shear strength, and energy absorption capacity [26]. Combined fibres of different types, geometric, volume fraction, modulus, and orientation, have improved RC and Engineered Concrete Composite (ECC) beam shear performance. Therefore, the available fibre combinations found in the literature and their impacts on the shear disposition of RC beams are reviewed in this section. In addition, the summarised data on combined fibre influences on the shear behaviour of RC beams are shown in Table 3, depicting the fibre combination type, volume, concrete grade, application and findings.

### 3.1 Polyvinyl Alcohol (PVA) and Polypropylene (PP)

There are some reports on PVA-PP hybrid fibre and ECC composites in RC beam shear performance. [52] examined fifteen RC beams made of polyvinyl alcohol (PVA), polypropylene (PP), and combined fibres that were evaluated through experiment and finite element analysis (FEA) procedures. In beams strengthened with and without shear reinforcement, the fibres were employed up to 2.5% and tested under four-point bending. It was observed that the RC beams containing PP, PVA, and their hybrid fibres demonstrated superior ductileness based on several fissures preceding failure, comparatively to the reference beam made of stirrups, devoid of fibres. Shear capacity and ductility are enhanced by a combination (1.5% PVA+0.375% PP) without stirrups, compared with reference beams with stirrups devoid of fibres. Figure 5 shows the combined fibres with stirrups and control, while Figure 6 shows the fibre combinations devoid of stirrups and the reference samples. It was concluded that shear strength and higher ductility were recorded with limited and optimum fibre combinations (0.75% PVA and 0.75% PP) and stirrups (7.5ø 6/m), compared to beams without stirrups, with 2.5% of PVA, PP single use or combined fibres (1.5% PVA+0.375% PP). The crack and failure mode of the beam (0.75% PVA+0.75% PP) +Stirrups is shown in Figure 7, compared with the beam (1.5% PVA+0.375% PP), without Stirrups shown in Figure 8.

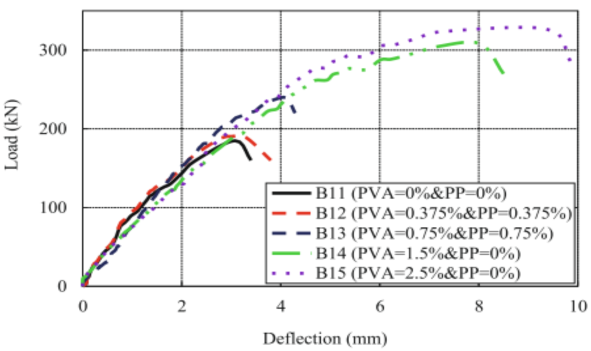



**Figure 5:** Combined fibres with Stirrups and Control [55]

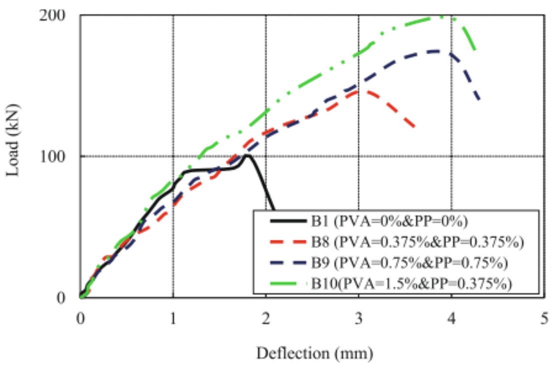



**Figure 6:** Combined fibres without Stirrups and Control [55]


**Figure 7:** Cracks and failure mode of a beam with (0.75%PVA+0.75% PP) +Stirrups [55]

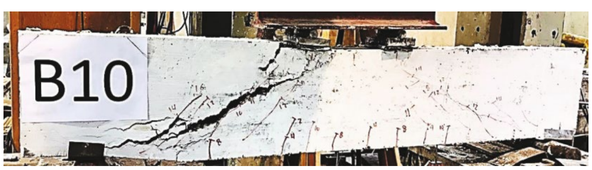



**Figure 8:** Cracks and failure mode of a beam with (1.5%PVA+0.375%PP), without Stirrups [55].

Similarly, Maheswaran et al. [56] studied the shear conduct of novel ECC beam members using a hybrid mixture of PVA and PP fibres devoid of strength and ductility compromise. Test samples were manufactured using four different mixtures configurations, including 1% of PVA and PP fibres, compared to 2% of steel, PP, and PVA. ECC beams with various fibre pairings were tested in an unbalanced three-point bending arrangement at a low shear span to an adequate depth ratio of 3.2 to restrict the shear failure to one side of the beam. The test result shows that, compared to steel and PP-fiber-blend ECC beams, total shear strength and ductileness were upgraded with PVA and PP hybrid. Combined fibres in ECC beams resulted in a greater critical shear crack angle and translation of collapse mode from inelastic diagonal tension to elastic bending. This is because flexure cracks caused Hybrid ECC beams to fail. The shear span can experience multiple flexure cracking, as shown in Figure 9, as load levels rise. A significant diagonal or shear crack was seen at 75% of the peak load in the shear span. However, the shear crack could not open up and go any wider due to the hybrid fibre combination. As a result, Figure 9 illustrates the widening of the flexure-shear fracture in the shear span. The compression zone saw severe concrete crushing as this flexure-shear fracture spread there. Due to the energy dissipation caused by the fibre crack bridging mechanism, it was discovered that the failure of ECC beams was more ductile than that of ECC beams with mono fibres.

The joints between the beam and column are where the forces from the adjoining beam and column are transmitted in RC-framed structural elements. The most susceptible area of the moment-repelling frame (MRF) structures prone to earthquake stress are the joints, which are prone to shear forces, among other forces. The joint's aversion potential depends on the collective activities of longitudinal and shear strengthening [57]. Therefore, Chidambaram and Agarwal [44] studied six high-performance, fibre-reinforced cementitious composites of external beam-column joints with various concrete mixtures subjected to cyclic loading with ECC with hooked-end steel, brass-coated steel, and PP fibre. Joint samples with Hybrid Cementitious Composite (HCC) demonstrate greater damage forbearance capacity than normal samples at higher rotations. It suggests that using HCC at the joint area would be a state that the shear capacity, impairment tolerance capacity, and element deformability would be greatly enhanced.

Some researchers have explored the hybridisation of various synthetic fibres in the shear performance of RC beams. To shift the failure mode in shear for concrete without stirrups from brittle to ductile. The study by Navas et al. [58] on the shear behaviour of RC-containing PP macro-synthetic fibres demonstrated that the macrofibres function as a reliable method of shear transfer in concrete. Zainal et al. [59] also investigated the potential for hybridising numerous synthetic fibres to enhance the shear-resisting properties of traditional concrete, mainly for reinforced concrete constructions in seismically active areas. This was accomplished by combining 16 different hybrid fibre-reinforced concretes (HyFRC) made from Ferro macro-synthetic fibres, Super-Net, Ultra-Net, Econo-Net, and Nylo-Mono microfibre. They were put through a direct shear test, and the controlled specimens' shear strength was increased by Ferro-ultra (32%), Ferro-super (24%), Ferro-Econo (44%), and Ferro-nylon (24%). It was shown that when the volume fraction of Ferro fibres increased, the shear strength increased as well, enhancing the cement matrix's capacity to take in shear energy. The direct shear applied to the prisms enabled the fibres to move like dowels during the fiber-bridging effects. As a result, factors such as fibrillation type, tensile strength, bonding power, and fibre length had a limit on how distinct microfibers affected hybridization. In conclusion, all of the hybrid fibre tested in this investigation demonstrated favourable synergistic action during direct shear at considerable fracture deformations.

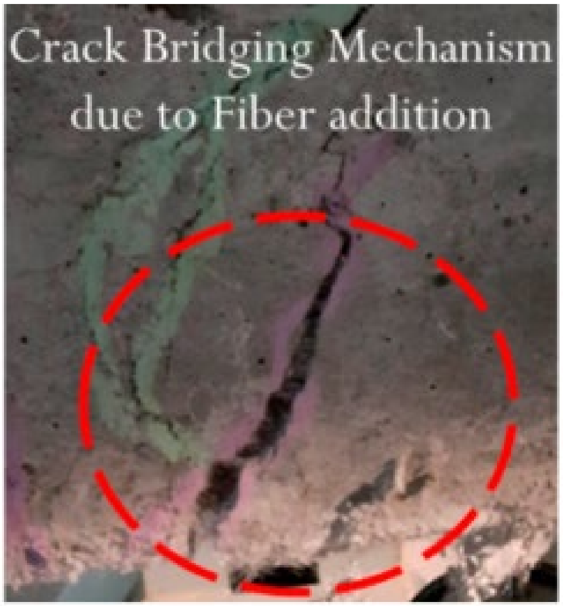



**Figure 9**: Combined (PVA +PP) effect on ECC beam failure mode [44].

### 3.2 Polyethene Terephthalate (RPET) And Polypropylene (PP) And Scribbled Steel (ST) Fibre

Also, synthetic and steel fibres have been combined synergistically to enhance RC beam shear strength. Karthik and Maruthachalam [42] researched the shear cracking behaviour of grade 40 hybrid FRC beams using a 0.5% volume mixture of RPET, PP, and scribbled steel (ST) fibre. The shear performance was investigated for concrete made with various hybrid fibre combinations, such as ST-PP and ST-RPET. The designed dosages are 0-100, 25-75, 50-50, 75-25, and 100-25. It was observed that synthetic fibres prevented the development of microcracks, but the inclusion of steel fibres often promoted bridging activity. The hybrid FRC performs better in shear in the ST-PP combo than the ST-RPET combo because there is a poor affinity between steel and RPET, compared with steel and PP. The best result obtained (ST75-PP25) combination shows that the allowable strength of RPET fibre is significantly less than that of steel and PP fibre combo. In another vein, Li et al. [60] studied the optimal combination fraction of fibres in hybrid fibre-reinforced concrete (HFRC) for tunnel construction. The hybrid fibres' optimal unit weight was discovered through parametric research on the enhancements of various fibre compositions on the shear strength and toughness qualities of HFRC. The ideal combination of 180 $Kg/m^3$ steel fibres and 4.5 $Kg/m^3$ basalt fibres substantially enhanced the direct shear strength by about 116%, shear toughness, and residual shear load. Steel fibre predominantly contributed to the direct shear strength compared to basalt fibre. Also, Polyvinyl alcohol and steel fibres were hybridised [61], which enhanced cementitious matrix performance in post-crack conditions.

### 3.3 Crimped steel-PP Fibres

The hybrid fibre volume also significantly impacts RC beams' shear behaviour. [62] investigated and reported how mixed fibres affect flexural components' shear strength from grade 55 ternary geopolymer concrete (TGPC). The shear strength of 27 (100x150x1200)mm beam size with crimped steel and PP fibres of 66 and 300 aspect ratio, respectively, were tested. The volume fractions of steel fibres (0.5 and 1%) and PP fibres (0.1%, 0.15%, 0.2%, and 0.25%) are crucial in this experiment. Comparing the Hybrid Ternary Geopolymer Concrete (HTGPC) and TGPC beams with and without fibres, it was found that the addition of hybrid fibres upgraded shear strength and switched the failure mode of the beam from shear to flexure. HTGPC samples with (1% SF+ 0.15%PP) performed better and experienced greater deflections, demonstrating a relative increase in ductility compared to other samples of higher volume fractions. Also, HTGPC beams outperformed TGPC beams in terms of first crack load and ultimate shear strength by up to 85% and 38.5%, respectively.

In addition, apart from volume fractions, the aspect ratio and the fibre anchorage circumstances could determine the shear strength enhancement. Smarzewsk [51] conducted research using hybrid fibre for shear reinforcement to improve reinforced HPC beams with apertures (BO1-BO3) and without (B1–B3) using hybrid steel–PP fibre as a strengthening option. Six simply supported 200 x 400 mm cross-section beams 2500 mm long were put through four-point bending testing. Traditional steel bar reinforcing was used to build Beams B1 and BO1. Fibre reinforcement with varied fibre volume contents was used for the remaining beams instead of stirrups and compressive bars. Incorporating hybrid fibres boosted the first cracking load, maximum stress capacity, toughness, and ductility compared to standard RC beams while lowering the average crack spacing, fracture breadth, and stresses. The fibres in B and BO beams at least 1% and 1.6% in quantity showed the best gains. The maximum stress fell for beams B2 and BO2 with the lower fibre content, and the failure mode shifted to sudden shear. The test findings demonstrate that when fibre content increases, the initial diagonal fracture and the ultimate shear strength are dramatically heightened, proving that hybrid fibres benefit from shear strength by narrowing the crack. It can be concluded that fibre volume fraction remarkably impacts beam shear conduct.

Furthermore, Sahoo et al.[47] studied how the volume proportion and kind of fibres in the concrete mix affected the shear strength of RC beams. Six FRC beam samples and one RC (control) beam specimen were tested with gradually increasing monotonic stress. Shear stirrups in the half-span of the FRC samples are eliminated by using 0.5% or 1% volume fractions of high-modulus (steel) and low-modulus (PP) fibres in concrete. Without shear stirrups, the FRC Sample with 1% PP fibres had peak shear resistance and mid-span displacement that were only around 70% and 50% of what they were for the RC samples, respectively. It is worth noting that the samples with hybrid steel and PP fibres of 0.5% reached the same shear strength as those without shear reinforcement. However, the shear resistance values of the concrete mixture (1 %PP and 1% SF) were enhanced by 20%. Several tiny cracks are seen in the CFRC samples at the failure stage, indicating the improved fibre-bridging activity of mixed metallic and nonmetallic fibres. However, it was concluded that steel and PP fibre should be included in the mix in an equal volume fraction for better shear aversion and deformability, with efficient stress redeployment at the failure phase.

### 3.4 Long Steel, Short Steel and PVA Fibres

Based on the above combination, apart from the fibre anchorage state, volume fraction, and aspect ratio, the fibre length equally influences the shear strength of the RC beam. The deep beam is characterised by shear failure rather than flexure failure, and it has been reported extensively in the literature that the shear capacity of RC deep beam rises as the concrete strength increases [63,64]. Ma et al. [19] studied the shear performance of Hybrid Fibre Reinforced Concrete deep beams. These beams' shear capacity tests were conducted on four HFRC deep beams and one RC deep beam. The characteristics of the steel fibres used are shown in Table 2. It was found that due to long fibres with strong pullout resistance, more energy would be lost when big cracks in the shear span occurred. For HFRC deep beams, the crack expansion is postponed, and the bearing capacity is increased. Short and long fibres complement one another during the deep beam failure, significantly increasing the load-carrying and deformation capacity. A better transfer of the internal forces was made possible by the HFRC deep beams' remarkable transformation.

The synergy of the combined fibre was improved by using a different type of metallic fibre. The hybrid steel fibres substantially enhanced the shear conduct of deep beams by increasing the ultimate load and preventing deep beam cracks from forming, reducing the number of shear reinforcements. Many diagonal cracks developed in the deep beams due to the hybrid fibres, improving fracture toughness. The maximum load and distortion of the HFRC deep beams with a similar web reinforcement ratio were superior to the RC deep beam. The most effective toughening resulted from adding 1.5% long steel fibres and 0.5% short steel fibres. The reason is that when various steel fibre lengths are combined, the short fibres, known as "micro reinforcement," primarily reinforce the cement matrix and restrain microcrack spread [19], thereby effectively improving the deep beam crack resistance.

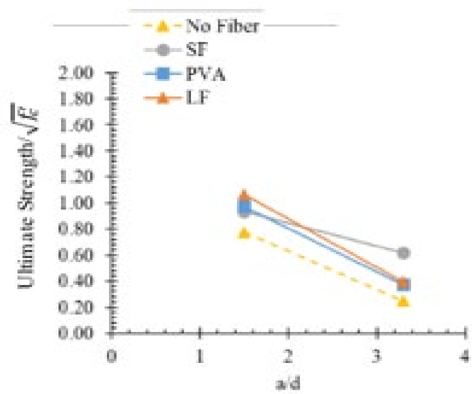
Furthermore, the current design standard mandates a dense arrangement of steel strengthenings for shear-prone elements like coupling beams and beam-column joints. This results in crowded strengthenings in such elements during construction, which can significantly lengthen construction time and lower building quality. One of the reasons for the synergistic application of fibres in the shear-susceptible structural elements is to reduce stirrups usage. Thus, Hung and Bermudez [65] explore whether using hybrid fibres in Ultra-High Performance Concrete (UHPC) can lessen stirrup usage in shear-prone structural parts. Four-point loading was used to test a variety of UHPC beams reinforced with longitudinal steel bars and various types of hybrid fibres(short-hooked-end steel, long, hooked steel, and PVA fibres. Other fibre properties are shown in Table 3. The impact of fibre combinations on the shear behaviour of the beam member was assessed using two different shear span-to-depth ratios. The test findings revealed that the samples with hybrid fibres had higher shear cracking stress, ultimate shear stress, and crack width control potential than beams with single fibres. Figure 10 shows the effects of fibre volume ‘$V_f$’ and the shear span-to-depth ratio on the ultimate shear strength for beams using combined fibres. As shown, the ultimate shear strengths of the hybrid fibre beam samples for both short and long beams were at least 1.8 and 2.8 times higher than the reference beam samples devoid of fibres.

Compared to other combinations of hybrid fibres, the hybrids of short and long steel fibres in the beams (150SF+75LSF) produced the best synergy and the highest ultimate shear strengths, as shown in Figure 10 (a, b and c). However, adding more short fibres than long fibres upgraded the maximum shear strength in the hybrid composite. PVA had no substantial effect on the synergy.

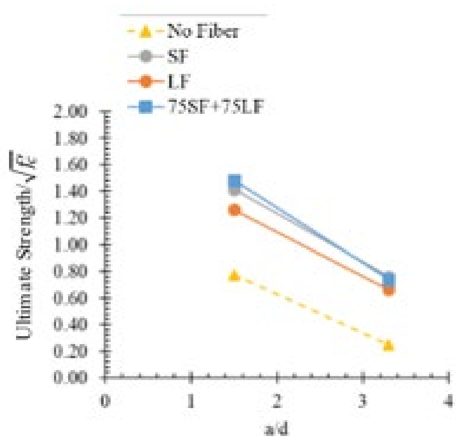
**Table 2:** Characteristics of Steel fibres used by Ma et al. [19]

| Types | $l_f$ (mm) | $d_f$ (mm) | $E_f$ (GP) | Tensile Strength (MPa) | Shape |
|---|---|---|---|---|---|
| Long steel fiber | 30 | 0.55 | 210 | 1345 | Hook |
| Short steel fiber | 13 | 0.20 | 210 | 2000 | Straight |

$l_f$ is the length of steel fiber, $d_f$ is the diameter of steel fiber, $E_f$ is the elastic modulus of fiber.




( a ) $V_f$=0.75%




( b ) $V_f$=1.5%

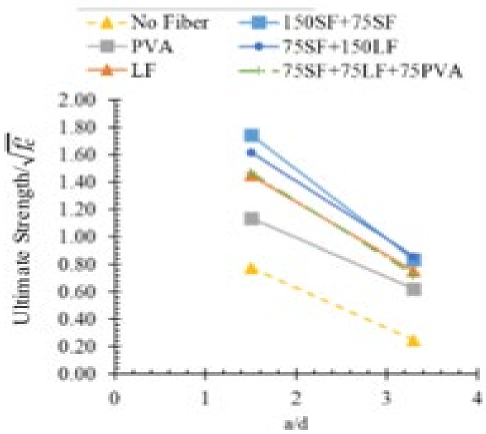



**Figure 10:** (a, b and c)- correlation between the volume fraction and the ultimate shear strength of beams with hybrid fibres [65].

### 3.5 Metallic and Plant-based Combination

Plant-based fibrous concrete has been explored for decades, and its behaviour in FRC beams has also been reported. Few reports on the hybrid of metallic-natural fibres in the shear performance of FRC are available in the research database. Nevertheless, they are well-explored in the current discussion. Banthia et al. [43] investigated and reported the combined impacts of hybrid macro-ST and micro-cellulose fibres on FRC's direct and flexural shear tests at 1% fibre volume fraction. The study used micro cellulose fibres with varied fibre ratios of hooked-end ST and DD ST fibres with a 16 m diameter and 2.3 mm length. In all samples, it was discovered that ST and cellulose fibres cooperated to produce positive results. Comparing the hybrid form of the micro-cellulose fibre to the cellulose fibre that contains FRC, the micro-cellulose fibre represents a significant provider of toughness. The blend of Hooked-End ST fibre and cellulose fibre significantly improved due to the stiffer fibre-matrix bond of HE Fibre. However, the coacting influence of cellulose fibre reduced as the deflection increased because, at larger crack openings, cellulosic fibre lost bridging capacity.

Also, Mohsin et al. [49] studied the effect of kenaf and steel fibre combinations on reinforced concrete beams. Four-point bending tests were conducted on six beam samples to examine the beams' structural behaviour while considering two parameters; shear reinforcement organisation and the kenaf and steel fibre fraction volume. Three of the six beams in the experimental study have full shear reinforcement applied with fibres at volume fractions of 0, 1, and 2%, respectively. The other three beams were evaluated with less shear reinforcement supplied with fibres with volume fractions of 0, 1, and 2%. The control beam was chosen because it has full shear reinforcement with steel and zero kenaf fibre. The result shows the possibility of improving load-bearing ability (up to 29%), ductileness (up to 22%), and controlled fracture propagation for the beams with 1%. Also, adding fibres transforms the beam's brittle failure mode into a more flexible one.

## 4.0 THE APPLICATION OF FIBRE FOR STRENGTHENING AND REPAIRING REINFORCED CONCRETE BEAMS

FRP composites are a popular strengthening method for Reinforcing Concrete (RC) members that work to withstand tensile pressures where required because structural materials are deteriorating, design loads are upgrading, and seismic, corrosion and fire damage may become inevitable. In RC beams, reinforcement corrosion can cause substantial harm and lead to durability failure of the structure [66]. Some studies on fibre's remedial and reinforcing capability in RC beams are available in the literature. According to Jongvivatsakul et al. [67], corrosion degree (0%, 12%, and 17%) and the volume of steel fibre in the SFRC (1.0%, 1.5%, and 2.0%) are used to investigate the shear behaviour of repaired corroded RC beams. While the shear capacity of the beam with the corrosion degree of 12% was lower than that of the uncorroded beam, that of the beam with the corrosion degree of 17% was higher. The test results show that corrosion level significantly impacts beams' shear-resisting capability, and the shear effectiveness of damaged beams is possible by mending them with SFRC containing sufficient steel fibres.

Similarly, Hong Bui et al. [68] used SFRC to repair damaged reinforced concrete beams in a flexural model. Before using SFRC in the flexural zone (tension region), eight RC beams underwent a corrosion procedure. The structural performances of the rebuilt beams were then examined using four-point bending tests and computer simulations. Experimental research validated the models' predictions of the shear-bearing capacity, load-deflection relationship and steel-SFRC/steel-concrete bond profiles. The analysis showed that the highest degree of corrosion-exposed SFRC beams repaired with 2% steel fibre volume could withstand the most significant crack openings. Due to the tensile reinforcement's tendency to give way, the failure of the SFRC-repaired beams tended to change a brittle shear failure into a ductile failure. The bonding power between

**Table 3** illustates the major finding from literature.

| | Author&Year | Fibre Type | Volume Fraction(%) | Other fibre properties | Beam size(mm) | Concrete Type/grade | Test Method/ Analysis | Application | Major Finding |
|---|---|---|---|---|---|---|---|---|---|
| 1 | [30], 2008 | SHE, SFH & PP | 0, 1 | | 100x100x350 | FRC beam/50 | Exp.& Analytical | Material | The fibres enhanced the toughness and shear crack resistance of the material, but 1% of fibres yielded lower shear strength than conventionally stirrup-reinforced beams with the same fibre content. |
| 2 | [29], 2014 | MS, MC | Steel: 0.3, 0.5, C: 0.5 | | 100x100x350 | FRC beam | Exp. | Material | for single fibre, hooked-end performed better in shear than double deformed composite. Under direct shear, no synergy of fibre type and hybrids; positive synergy was observed with an increase in shear deformation |
| 3 | [31], 2015 | Steel-PP | 0.5, 1 | 12.5(l), 0.5(D), (a/d) = 25 | 150x200x2000 | FRC beam | Exp. | Beam | combined steel and PP fibres, with content as low as 0.5% in the concrete, reached the same shear strength as RC samples without shear stirrups. Shear resistance was enhanced by 20% when PP is 1% |
| 4 | [51], 2015 | SBS, RPET, PP | 0, 0.5 | (l/d)=50, 1900, 830 | 150x200x7000 | FRC beam/40 | Exp& Numerical | Beam | The addition of steel fibre helped in bridging action, while synthetic helped delay microcracks, but the steel-PP combination has better performance. |
| 5 | [32], 2015 | Steel | 0, 2 | | 130x350x1800 | NSC- 40-50, HSC- 80-100 | Exp. | I-beam | Fibre type remarkably affects shear behaviour; a combination of high and low-strength fibres is insignificant in shear performance. |
| 6 | [4], 2016 | Steel, Kenaf | 0, 1, 2 | | 150X150X1500 | FRC beam | Exp. | Beam | The outcome indicates that for beams with 1%, there is potential for improving the load-bearing ability (up to 29%), ductileness (up to 22%), and controlling crack propagation. |
| 7 | [34], 2018 | Steel, MSP | 0.35, 0.7&1.0 | (a/b)= 5 | 200×300×3500 | Presstressed | Exp. | Beam | The beam failure state transformed from an inelastic flexure-shear to a more ductile flexure-controlled state at 0.35& 0.70% vol. dosage of steel and synthetic fibres |
| 8 | [17], 2018 | Steel-PP | Steel: 0.5,1,1.5 PP: 0.025, 0.05, 0.1 | | 200X400X2500 | HPC | Exp. | Beam | Results reveal that the initial diagonal break and the final shear strength increase dramatically as fibre content rises. |
| 9 | [52], 2021 | PVA, PP | PVA-0, 1, 1.5, 2.5, PP0,1,1.5,2.5, hybrid-(0.375&0.75) | (a/d) =2.25 | 120x300x1800 | FRC | Exp, Theoretical&FEM | Beam | A blend of (0.75% PVA and 0.75% PP) fibres and shear links (7.5 6 /m) should be employed to obtain sufficient shear performance of hybrid FRC beams. |
| 10 | [46], 2021 | Steel-PP | Steel: 0.5,1 PP: 0.1, 0.15, 0.2, 0.25 | | 100×150×1200 | HTGPC/55 | Exp. | Beam | Compared to TGPC beams, HTGPC beams' initial crack load and ultimate shear strength increased to 85% and 38.5%, respectively. |
| 11 | [38], 2022 | Steel, PVA, PP | 0, 2 | (l/d): PP=910, PVA=300, Steel=60 | 100×150×1200 | ECC | Exp.& Numerical | Beam | In ECC beams, hybrid fibre escalated the crucial shear fracture angle, showing a failure transformation from inelastic diagonal tension to ductile flexure. |

the corroded steel and SFRC decreased as corrosion intensity increased, and the simulation's effectiveness was dependent on the features of the material constitutive models and shear crack transmission coefficients. Also, Jongvivatsakul et al.[69] used experimentation, analytical computation, and numerical analysis to examine the shear behaviour of RC beams reinforced with SFRC panels. To test the influence of fibre volume content, connecting type, and the quantity and diameter of bolts on the strengthened RC beams' structural reactions, SFRC panels mounted to both sides of the beams underwent an experimental program. According to the empirical findings, utilizing SFRC panels to strengthen beams significantly increases their shear effectiveness, and the testing and analytical results are in good accord. A shear-resisting model with sufficient precision is proposed based on the numerical and experimental analysis, and it incorporates the straightforward formulation of the average tensile strength perpendicular to the diagonal crack of the strengthened SFRC panels.

In addition, Jongvivatsakul et al. [70] investigated repairing corrosion-damaged concrete beams with aramid fibre-reinforced composites, and how the fibre geometry affected the mechanical characteristics of AFRC was determined. According to the test results, a fibre length of 40 mm is ideal for enhancing the tensile strength of AFRC. Additionally, twisted fibres have a higher load resistance capacity in the post-peak regions than single fibres. Both RC beams with and without repairs were tested using a four-point bending load, and the results showed that a corroded RC beam that had been rebuilt using aramid fibre-reinforced mortar had almost as much load capacity and ductility as a non-corroded RC part. The corroded beam's mended aramid fibre-repaired cracks had much smaller crack widths**.** Thus, these studies indicate fibres' remedial and reinforcing effectiveness in RC beams.

## 5.0 CONCLUSION

The essence of fibre hybridisation is to explore individual fibre types to enhance the shear performance of RC beams, which is obtained according to ultimate shear energy to shear deflections. In hybrid FRC, the excellent relationship between the fibres outweighs the sum of their mono-fibre characteristics. The construction industry is facing a severe issue with RC beam shear failure. This is because failure due to shear is disastrous, and its occurrences are frequently devoid of prior notice; the beam should collapse in flexure instead of shear. This beneficial effect results from the sliding resistance posed by the fibres positioned between shear crack surfaces and depends on several fibre factors, like; content proportion, aspect ratio, distribution within the concrete mix, and orientation along the cracked surface. Finally, the findings indicate a remarkable impact of hybrid fibres on shear strength under loading due to the synergistic function of an individual fibre in composite compared with a single fibre. These findings are summarised as follows.

- Adding an excess of 1.5% PVA or combined (PVA & PP) in a proportion of (1.5% & 0.375%) increased the shear ability and ductility. However, combining a limited number of combined (PVA+PP) fibres in volume fractions of 0.75% and 0.75%, respectively, and shear links improved shear strength and higher ductileness.
- For ECC, in comparison to the Normal Concrete beam, all ECC beams performed better in terms of cracking activity, shear capacity, and ductility. The beam with 8% of PVA has the greatest shear strength and ductileness compared to all ECC beams of other synthetic fibres.
- For beam-column joints, Hybrid Cementitious Composite (HCC) was recommended at the joint area for a substantial increase in the shear capacity, impairment forbearance ability, and member ductileness. Also, the steel (75%) & PP (25%) combo addition offers the best performance compared to RPET fibre.
- The review shows that when fibre content increases, the initial diagonal fracture and the ultimate shear strength dramatically increase, proving that hybrid fibres benefit from shear strength by narrowing the crack.
- The specimens with hybrid steel and PP fibres 0.5%Vf reached the same shear strength as those without shear reinforcement. However, shear resistance values of concrete mixture with (1%$V_f$ of PP and 1% volume fraction ($V_f$) of steel fibre) were enhanced by 20%.
- Hybrid fibres significantly influence how deep beams behave when they are sheared. The sample with 1.5% for the long steel fibres and 0.5% for the short steel fibres performed the best. Combining several steel fibre types or varying lengths boosted the synergetic effect.
- For the steel-natural fibre combination, there is a possibility of improving load-bearing ability by 29%, ductileness by 22%, and controlled fracture propagation for the beams by 1%. The hybrid of steel and cellulose fibre was possible due to the stiffer fibre-matrix bond of steel fibre. Nevertheless, as the deflection rose, cellulose fibre's coacting effect decreased cellulose fibre lost its ability to bridge bigger crack holes.
- The resilience of the matrix is unaffected by the inclusion of cellulosic fibre, although it improved toughness when steel fibre was also introduced. Double-deformed steel fibres perform better in direct shear than hooked-end steel fibres, which are more effective in flexural strengthening when coupled with cellulosic fibres. The findings indicate a remarkable impact of hybrid fibres on shear strength under loading.
- Fibres proved effective in shear performance upgrades and remedial and strengthening corroded RC beams.

## 4.0 FURTHER RESEARCH

- More research should be carried out on the effect of varying lengths and diameters on the shear performance and ductility based on a hybrid system.
- More numerical and analytical tests should be conducted to confirm the experimental, especially the new and innovative fibre combinations.

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