CHAPTER – 2

LITERATURE REVIEW

This chapter reviews existing literature on research conducted in the proposed area, commencing with a discussion on textile structure, definition of TRC, composition of cementitious matrix for TRC manufacturing, TRC fabrication methods, hybrid yarn manufacturing methods and their advantages, 2-D woven fabric and the 2-D woven fabric parameters affecting TRC properties, non-crimp fabrics (NCFs), methods for improving fibre-mortar bonding – surface modification of FRP bar, modification in braided structure, and coating textiles- yarn and fabric coating and its influence in FRCM behaviour, inclusion of short fibres as secondary reinforcement in FRCM, mechanical characterisation of FRCM – strain-softening and strain-hardening response, yarn pull-out behaviour, uniaxial tensile, and flexural behaviour. Finally, gaps in the literature are mentioned.

2.1 Textile Structures

Plain (unreinforced) concrete is a brittle material with low tensile strain and strength capacities. Incorporating short, discontinuous fibres helps to strengthen and improve concrete toughness [39]. Textile materials, in various forms, are used as concrete reinforcement. These materials can be either continuous or discrete. Discrete forms, known as fibre reinforced concrete (FRC), involve short fibrous textiles of natural (jute, hemp, flax, coir, sisal, bamboo, kenaf, banana, and pineapple, etc.) or synthetic (polypropylene, polyester, nylon, and polyethylene, etc.), and high-performance (carbon, glass, basalt, aramid, poly(vinyl alcohol), polybenzoxazole, and steel) fibres are dispersed in the concrete [6]–[9], [22]. The important properties of the typical fibres used in concrete reinforcement are listed in Table 2.1.

The broad definition of FRC according to A.E. Naaman [40]

"Fibre reinforced concrete (FRC) is concrete with suitable discontinuous fibres added to it for the purpose of achieving a desired level of performance in a particular property (or properties)."

The addition of fibres to the concrete matrix improves its mechanical characteristics, enhancing post-cracking ductility, strain hardening, flexural rigidity, toughness, impact resistance, fire resistance and crack resistance through fibre bridging, resulting in improved durability [39]–[41]. However, fibre content should be limited to 3% to maintain workability and prevent agglomeration [10], [11], [22]. The quantity of fibres used depends on the type and geometry of the fibres as well as the specified end use. Fibres reduce the workability of concrete, necessitating the use of water-reducing and high-range water-reducing admixtures. Additionally, the use of fibres may require longer mixing times and must be added at a specific stage in the mixing process [41]. Longer fibres can create voids and result in poor bonding. FRC cannot fully replace primary reinforcement in slender elements when the fibre volume fraction exceeds 5% [12]. Additionally, achieving smooth surfaces and controlling fibre orientation with discrete fibres is challenging. In contrast, integrating yarns and textiles offers greater flexibility and allows for customized reinforcement compared to fibrillated film.

Table 2.1 Typical fibres used in concrete and their properties[42].

Fibre types	Relative density (g/cm^3)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Diameter (µm)	Ultimate elongation (%)	Operating temperature (℃)
Steel fibre	7.8	400 – 2100	154 – 200	300 – 800	3.0 – 4.0	<600
Basalt fibre	3.0	3000 – 5000	80 – 110	10 – 15	3.1	<700
Glass fibre	2.7	14 – 2800	70 – 90	8	2 – 3.5	<300
Carbon fibre	1.76	2450 – 3150	205	7 – 8	1	<500
Polypropylene fibre	0.91	400 – 650	5 – 8	43	18	<400
Polyvinyl alcohol fibre	1.2	1600 – 2500	40 – 80	39	6	<200 – 400
Polyacrylonitrile fibre	1.18	>600	>10	12 – 21	>15	<300
Polyethylene fibre	0.96	2850	73.9	35	10	<200 – 400
Nylon fibre	1.16	900 – 960	4 – 6	30	18 – 20	<250

Continuous textile assemblies, such as unidirectional and bidirectional fabrics (woven, knitted, non-crimp), nonwoven fabrics, fabric composites, fibre reinforced polymer

(FRP) laminates, braided rods, and FRP rods, are also used as concrete reinforcement [43]. Various forms of textile materials and structures used for reinforcing concrete are illustrated in Figure 2.1.

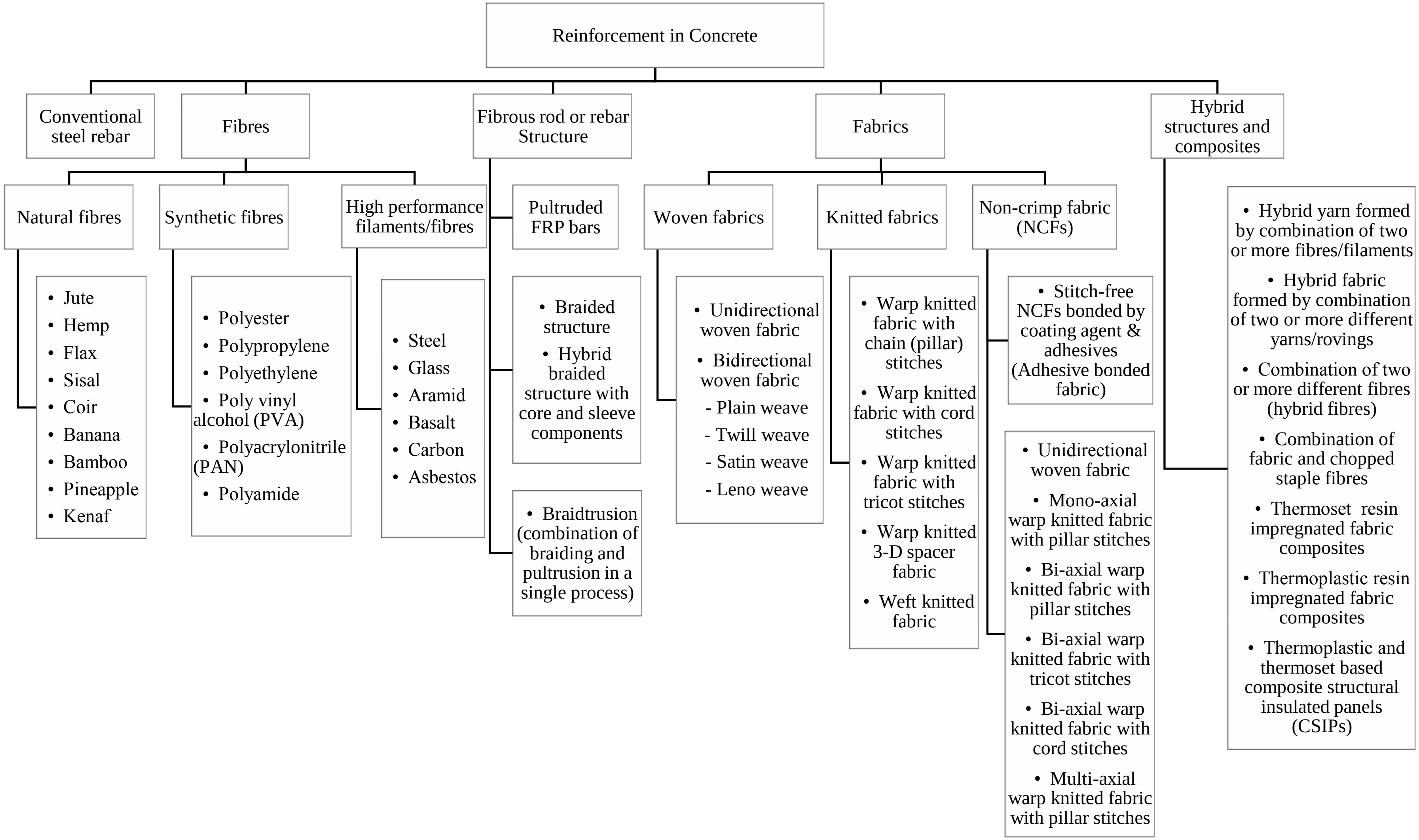


Figure 2.1 Classification of textiles and textile-based composites for reinforcement in concrete elements[43].

When comparing high-performance textile reinforcements (made with high-performance fibres) to steel reinforcements, the advantage of one over the other will likely depend on factors beyond strength or MOR. These factors may include weight, ease of handling, and life-cycle cost [44].

Figure 2.2 shows how combining a concrete matrix with continuous or discontinuous reinforcement has led to various structural composites developed since the mid-19th century, including the widely used reinforced and prestressed concrete [40].

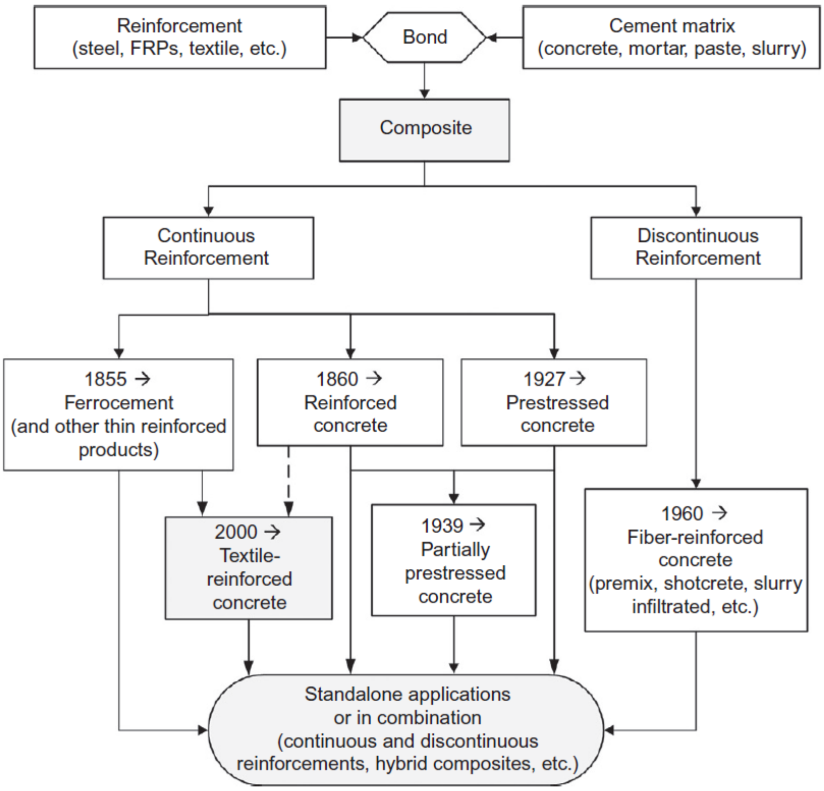


Figure 2.2 The evolution of different types of structural concrete composites[44].

2.2 Textile Reinforced Concrete

Textile reinforced concrete (TRC), also known as textile reinforced cementitious composite (TRCCs) or textile reinforced mortar (TRM) or fabric-reinforced cementitious matrix (FRCM), is a composite material composed of two essential components: a fine-grained cementitious matrix reinforced by one or more layers of continuous textile or fabric structure for reinforcement. A simple illustration of TRC is shown in Figure 2.3.

The general definition of TRC as per A.E. Naaman[44]

"Textile reinforced concrete is a type of reinforced concrete commonly constructed of hydraulic-cement matrix reinforced with several layers of closely spaced continuous 2D textiles, or one or several layers of 3D textiles. At least one textile layer should be placed near each of the two extreme surfaces of the resulting structure. The textiles may be made of polymer, synthetic, metallic, organic or other suitable materials. The fineness of the cementitious matrix and its composition should be compatible with the textile armature system it is meant to encapsulate. The matrix may contain discontinuous fibres or microfibres of appropriate dimensions."

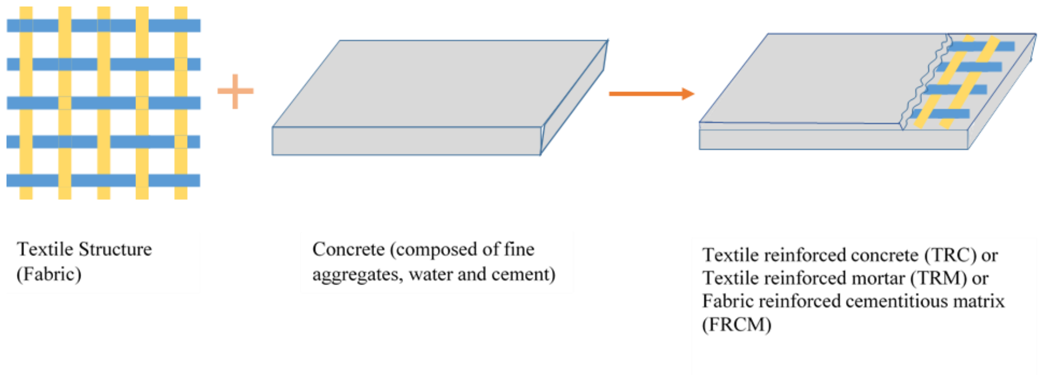


Figure 2.3 A simplified illustration of textile reinforced concrete (TRC)[43].

2.3 Composition of cementitious matrix for manufacturing TRC

Standard concrete is composed of a binder, fine aggregate, coarse aggregate, and water. However, depending on specific requirements, the proportions of these components can be adjusted, or alternative materials can be used. The cementitious matrix in TRC combines binder, fine aggregate, chemical admixture, and water, with a maximum grain size of around 2 mm, classifying it as fine-grained concrete or mortar [45]. Coarse aggregate is not used. The matrix should be chosen and prepared based on reinforcing fabric geometry, reinforcement type, component shape, and production method to achieve desired bond behaviour, mechanical properties, and durability [11], [45]. The mortar composition significantly impacts its effectiveness in TRM systems. Proper fibre impregnation by the mortar is crucial for strong bonding. Ideal mortar characteristics include fine granules, plastic consistency, workability, low viscosity for vertical surfaces, and adequate shear strength to prevent debonding. Cement-based mortars are commonly used for TRM matrices, with polymers enhancing mechanical properties like flexural strength and fibre roving bond [18].

Table 2.2 Composition of cementitious matrix used for manufacturing TRC used in various studies[33], [46]–[49].

Ingredients of cementitious matrix	Reference [46]	Reference [47]	Reference [47]	Reference [48]	Reference [33]	Reference [49]
Cement (kg)	567	583	674	577	480 (CEM 42.5 R)	589.2 (CEM 52.5R)
Water	180 l	-	-	330 kg/m^3	284 l	259.2 kg/m^3
Fly ash (kg)	104	208	114	206	240	189
Micro sand (kg)	204	-	-	-	642 (0-0.3 mm)	1121.6 (0.6-1.0)
Fine aggregate (Crushed stone) (kg)	264	-	-	943 (river sand)	503 (0.2-0.5 mm)	-
Coarse aggregate (kg)	1102	-	-	-	-	-
Silica fume (kg)	-	42	79	41		50.3
Quartz sand (kg)	-	595 (0.2-1.1 mm)	1037	-	-	-
Quartz powder (kg)	-	357 (20-160 µm)	207	-	-	-
Fibre (kg)	38.52 (GI 25 mm length)	-	-	-	-	-
Admixture	5.36	-	-	-	-	-
Water/binder	-	0.4	0.24	-	-	-
Superplasticizer – 1	-	0.15 PCE (% solid/binder by wt.)	1.3 PCE (% solid/binder bywt.)	4	10.8	0.016 (% wt. of binder)
Superplasticizer – 2 (% solid/binder by weight)	-	-	0.08 VMA	-	-	-
Slump height (mm)	270	-	-	-	-	280
Harden density of concrete (kg/m^3)	2371	-	-	-	-	-
Compressive strength (MPa)	62.11	60.2	104	55	52.3	113
Split Tensile strength (MPa)	4.05 MPa	-	-	-	-	-
Modulus of Elasticity (GPa)	-	27.1	34.6	-	-	-
Flexural strength (MPa)	-	7.2	11.8	-	-	-

2.4 TRM fabrication methods

Continuous fabrics are a versatile reinforcement for concrete, both in new construction and repair. They allow for precise tailoring of strength based on fibre orientation and fabric design. However, successful use requires careful consideration of material properties and processing techniques to optimize the bond between fibre and concrete [11]. The key factors during TRM fabrication involve both mortar and fabric properties. These include the cementitious mix design (particle size, rheology), fabric characteristics (grid opening, reinforcement type - 2D/3D structure, yarn size and coating), all influencing the final composite quality and bond between fibre and matrix [22].Processing conditions and fabrication techniques significantly influence reinforcement volume, uniformity, shape, and composite quality. A strong fibre-matrix bond is crucial for mechanical properties, requiring proper matrix penetration among fabric constituents. Aligning production processes with fabric structure and yarn optimizes bond efficiency [50].

2.4.1 Casting

In this method, a mould (formwork) is created to match the final concrete element's size and dimensions. The fabric is positioned or clamped inside the formwork at the specified depth and spacing using spacers. Fine-grained cementitious mortar with the desired flow consistency is then slowly poured into the formwork, ensuring the reinforcing fabric stays undisturbed. After 24 hours, the concrete specimen is removed from the mould and cured in water for 28 days (Figure 2.4).

In-place casting allows for quick manufacturing, high reproducibility, minimal errors, better surface quality, and the use of 3-D reinforcing meshes. However, if the fabric is densely packed or has low stiffness, the method can fail, resulting in poor matrix penetration, which can cause pores, cavities, and inadequate embedment of the textile reinforcement [51].The casting method is ideal for 2-D slabs and simple 3-D elements but requires extra effort for larger structures [52]. It can be used for beams, foundation beams, slabs, connections, floor elements, wall elements, barrel-shell vaults, and columns [53].

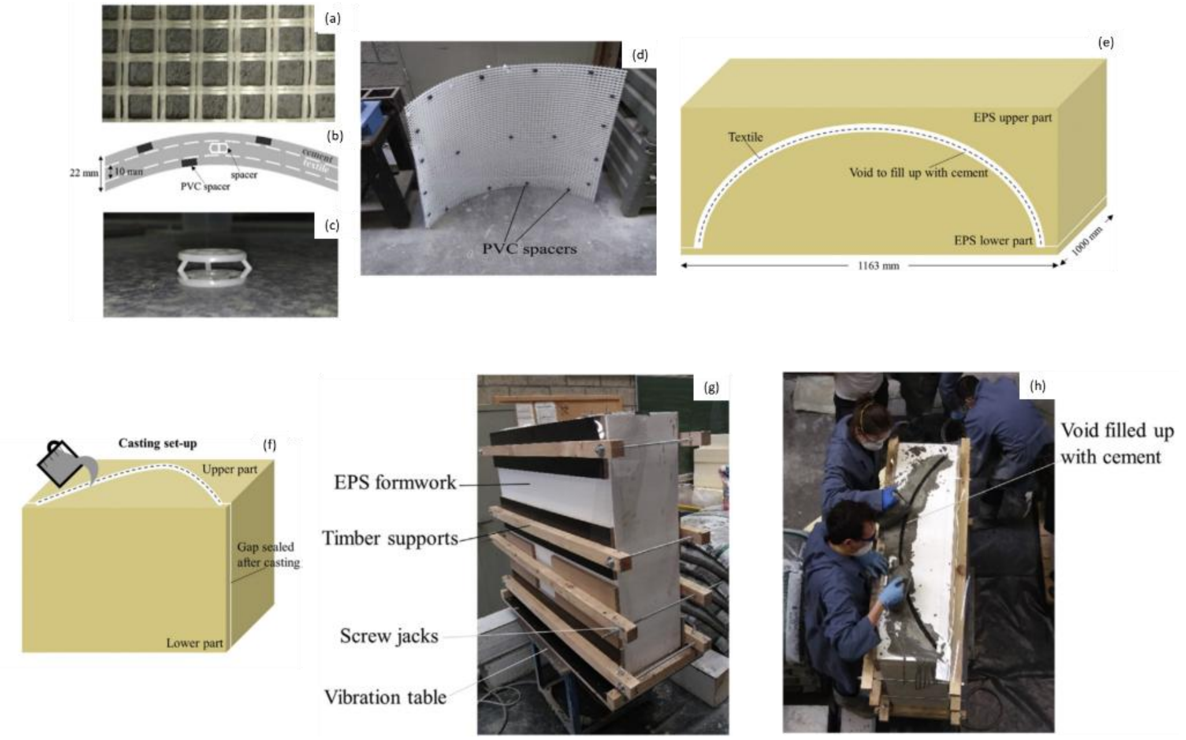


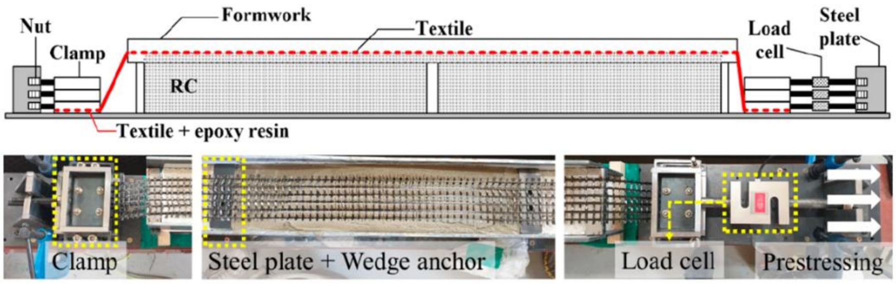
Figure 2.4. Sequential process demonstrating the casting of a TRC shell structure: (a) AR glass fabric, (b) Cross-sectional view of the shell element, (c) plastic spacers for maintaining consistent distance between fabric layers, (d) placement of PVC spacers to ensure uniformity between fabric layer and formwork, (e) two-piece formwork made from expanded Polystyrene (EPS), (f) vertical casting setup, (g) EPS formwork design with rebar-bolts system to control TRC thickness and prevent matrix leakage, (h) pouring of cementitious matrix into EPS formwork to cast TRC shell[54].

2.4.2 Pre-tensioning (Prestressing)

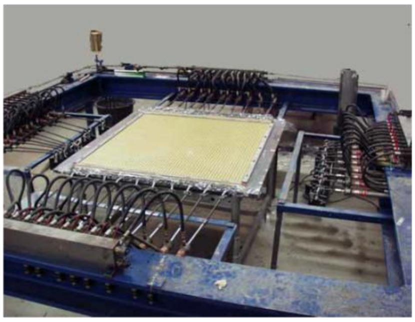
Prestressing, or pre-tensioning, improves the elastic state of brittle-matrix cementitious composites, counteracting concrete's low tensile strength. Typically, reinforcing steel cables or bars are tensioned to create compression forces that offset tensile loads during use [11], [55]. Fabric reinforcements are pre-stressed or pre-tensioned to eliminate waviness and align them with the reinforcing direction [55], [56], enhancing the load-bearing capacity and first crack stress of concrete elements [57].

Pre-tensioning can be done through chemical prestressing or mechanical fabric stretching. Chemical prestressing uses an expansive admixture like PCE20 (replacing 20% of the cementitious mix) to create compressive stresses in structural elements. Chemically pre-stressed specimens have better fabric-matrix bond behaviour and strength than non-pre-stressed ones due to increased density and adhesion surface [58].

In a uniaxial prestressing system, fabric ends are impregnated with epoxy resin for even load distribution through the clamp (Figure 2.5, a). Mechanical prestressing is achieved by tightening nuts after securing the fabric, with the force measured by a load cell. For biaxial prestressing, a rigid steel frame with hydraulic pistons is used, allowing transverse flexibility. Concrete is applied over the fabric and vibrated for compaction. After 24 hours, the piston pressure is released (Figure 2.5, b-c). The TRC specimen is then cured under wet conditions for 5 days before being stored at 20°C and 65% RH [55].



(a)



(b)

(c)

Figure 2.5 Pre-stressing technique: (a) uniaxial prestressing system for producing TRC elements[59], *(b) tensioning frame used in the manufacture of biaxially pre-stressed TRC panels, (c) application of concrete matrix onto pre-stressed aramid TRC panels*[55].

TRC specimens mechanically stretched show higher tensile strength, greater deformation at failure, and narrower crack widths compared to manually stretched textiles, where fabric debonding can occur [56].

2.4.3 Hand lay up

Hand lay-up, also referred to as contact moulding or hand laminating, is a commonly employed and economical technique for manufacturing elements using fibre-reinforced polymer composites. The procedure consists of four primary stages: preparing the mould, applying gel coating, hand laying the fibres, and finishing the product [11], [60] (Figure 2.6).

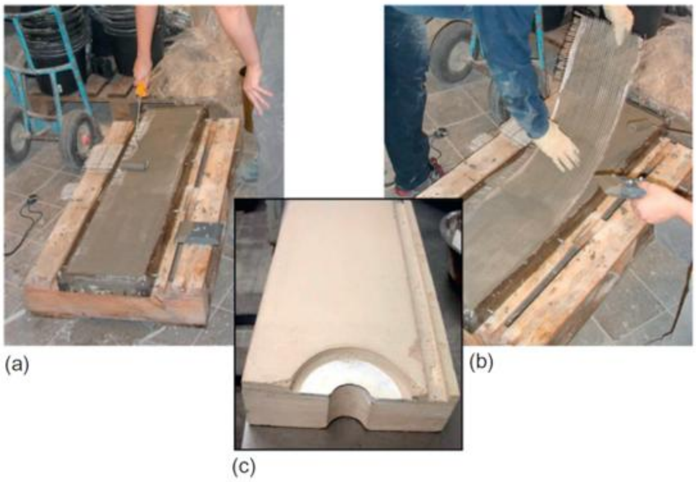


Figure 2.6. TRC slab created using hand lay-up method: (a) compaction of concrete layer using roller, (b) placement of fabric layer, and (c) underside view of the laminated[52].

TRC specimens can be moulded using this method with single or multiple layers of fabric, forming laminated composites. The process necessitates an open reinforcement grid structure to facilitate cementitious matrix penetration. This approach allows for a high fibre volume fraction in TRC, enhancing energy absorption and tensile strength. Hand lay-up offers straightforward fabrication technology and the capability to produce large, intricately shaped products. However, it has a slower production rate and demands skilled labour to ensure product quality [60]. While suitable for 2-D and basic 3-D slabs [61], it is less frequently used for 3-D fabric reinforcement [51].

2.4.4 Spraying method

Sprayed concrete, also known as 'Shotcrete,' is applied under high pressure onto a substrate to consolidate concrete. It can be wet-mix or dry-mix. The wet-mix process involves mixing materials before application and is increasingly preferred in tunnelling for its higher throughput, reduced rebound, and minimized health risks. Shotcrete finds widespread use in supporting rock in mining and tunnelling projects, as well as in structural repairs, soil stabilization, and other applications [62].

Shotcrete methods are categorized based on their components, including conventional, refractory, special, and fibre-reinforced types. Fibre-reinforced shotcrete integrates steel or synthetic fibres at a 1% volume fraction in the cementitious mix. When applied to a substrate, it boosts flexural strength, shear strength, fracture toughness, and impact resistance [63].

Additional fabric reinforcement enhances load-bearing capacity [60]. This spraying method is ideal for new structures, strengthening, repairs, and tunnel construction. Unlike high-pressure shotcrete, it operates at a lower pressure of approximately 8 bars [52].

This method begins with spraying a layer of fine-grained concrete into the formwork to create a base. Fabric is then placed over this layer and compacted using a roller. Another layer of fine-grained concrete is sprayed over the fabric. Finally, the structural component's surface is trowelled for finishing (Figure 2.7). This approach enables the production of TRC building elements in both horizontal and vertical orientations, achieving a high reinforcement ratio akin to laminating techniques [52]. Its benefits include cost-effectiveness, minimal formwork usage, high efficiency, and suitability for slender structures, sandwich elements, and complex designs like multi-curved shells [51].

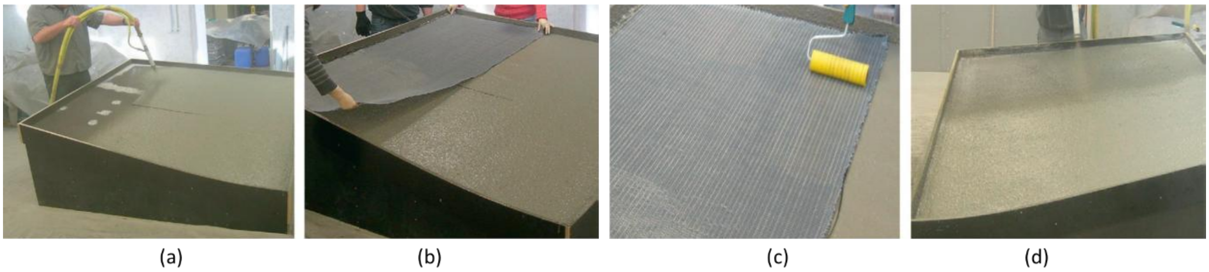


Figure 2.7 Spraying method: (a) application of the cementitious matrix layer by spraying, (b) placement of the fabric layer over the matrix, (c) compaction using a roller, (d) reapplication of the cementitious matrix layer[52].

2.4.5 Filament Winding

The filament winding technique uses continuous rovings to create thin cement composites with high fibre volume and various ply orientations [60]. The roving is unwound, coated with size, passed through rods for better separation and matrix penetration, then impregnated with cement slurry and wound around a rotating mandrel to form laminated composites with orientations of 0°, 90°, and 45° (Figure 2.8).

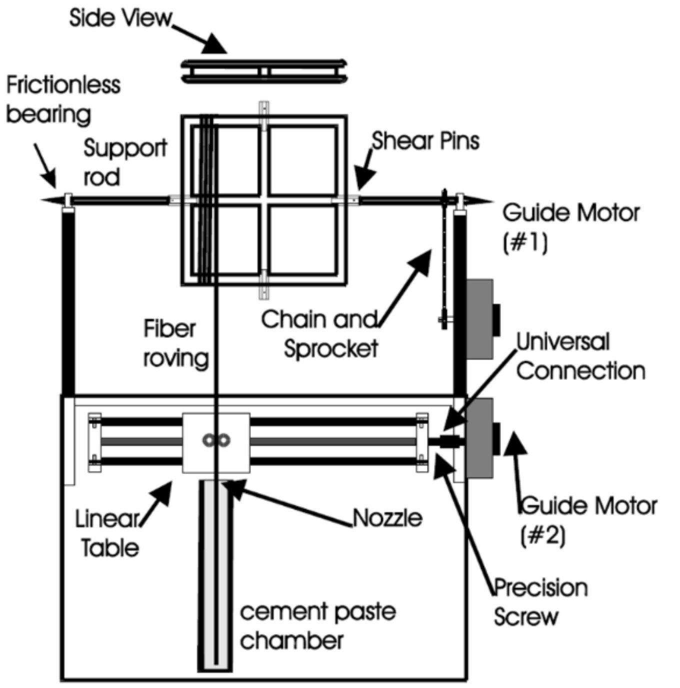
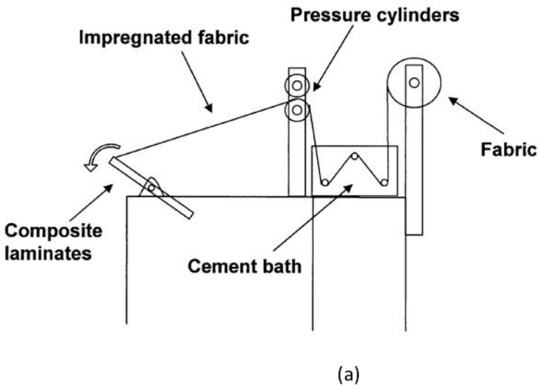


Figure 2.8 Schematic of filament winding method used for producing cementitious matrix impregnated laminated composite[64].

This method enhances mechanical properties and distributes cracking. It has been used to produce cross-ply laminated composites with PP and AR glass yarns in orientations like (0°/45°/90°), (0°/45°), and (45°) [11], [64]. AR glass composites showed improved tensile strength, strain capacity, toughness, and distributed cracking, though the ply interface layer remained a weak point [64]. This technique was later adapted to develop fabric-based laminated cement composites using the pultrusion method.

2.4.6 Pultrusion

Pultrusion is a method that produces fabric-cement products with a straightforward, cost-effective setup, ensuring precise alignment and smooth, uniform surfaces across the cross-sectional area [65]. Fabrics are saturated with fresh cementitious matrix and shaped into laminates on a rotating plate mandrel (Figure 2.9). The matrix must be sufficiently fluid for fabric infiltration yet dense enough to adhere well. Laminates undergo curing under pressure for 24 hours followed by room temperature curing for 25 days [14]. The penetration of the cementitious matrix and bonding behaviour in the composite are influenced by filament bundle and mesh sizes. Additives such as fly ash, silica fume, polymers, and short fibres can alter the viscosity and penetration capability of the fresh cement mixture.



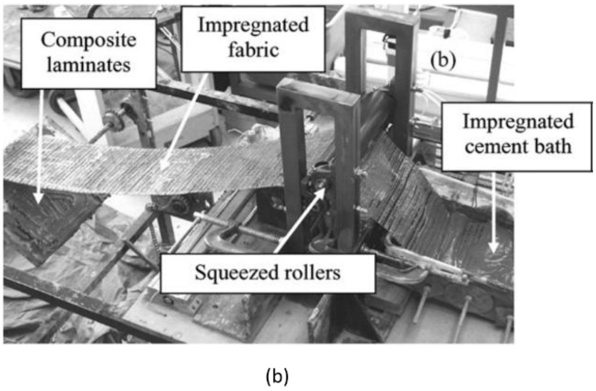


Figure 2.9. (a) Schematic representation of a pultrusion setup[66], *(b) actual photograph of the pultrusion process*[15].

Pultrusion yields uniform composites with enhanced tensile properties and resistance to multiple cracking [11]. This method has successfully produced laminated TRC composites with up to 9.5% volume of reinforcements [66]and 20 layers of fabric [67]. It accommodates various fabric types including woven, knitted, and bonded, using diverse fibre materials such as polypropylene, polyethylene, AR glass, carbon, aramid, PVA, and hybrids combining multiple fibre types [11], [68].

Pultrusion improves bonding, pull-out resistance, tensile behaviour, and reinforcement efficiency particularly in warp-knitted fabrics with weft insertion using multifilament bundles. However, it does not surpass casting for fabrics with coated bundles or monofilaments, primarily due to the absence of interstitial openings for fibre impregnation [50], [68].

2.4.7 Combined additive manufacturing of TRC

Combined additive manufacturing methods for concrete and reinforcement provide greater design freedom and improved bonding with surrounding materials. This approach eliminates the need for assembly reinforcement, resulting in more efficient and complex structural components. Achieving a strong bond between concrete and reinforcement is a key challenge. Techniques like controlling concrete consistency, using bonding mortar, or incorporating mineral-bound carbon fibre reinforcements can enhance this bond. Integrating reinforcement into 3D printing processes allows for diverse material combinations and printing methods.

Figure 2.10 illustrates the systematic approach for combined additive manufacturing of reinforced concrete, where concrete supports reinforcement and vice versa [69]. In the "Concrete Supports Reinforcement" method, freshly printed concrete acts as a support, allowing precise placement of reinforcement without additional rebar stirrups. Techniques include injecting short reinforcements orthogonally and pressing textile reinforcement into fresh concrete. In the "Reinforcement Supports Concrete" method, prefabricated reinforcement shapes the structure, with concrete printed or sprayed onto it, becoming an integral part of the final structure [70].

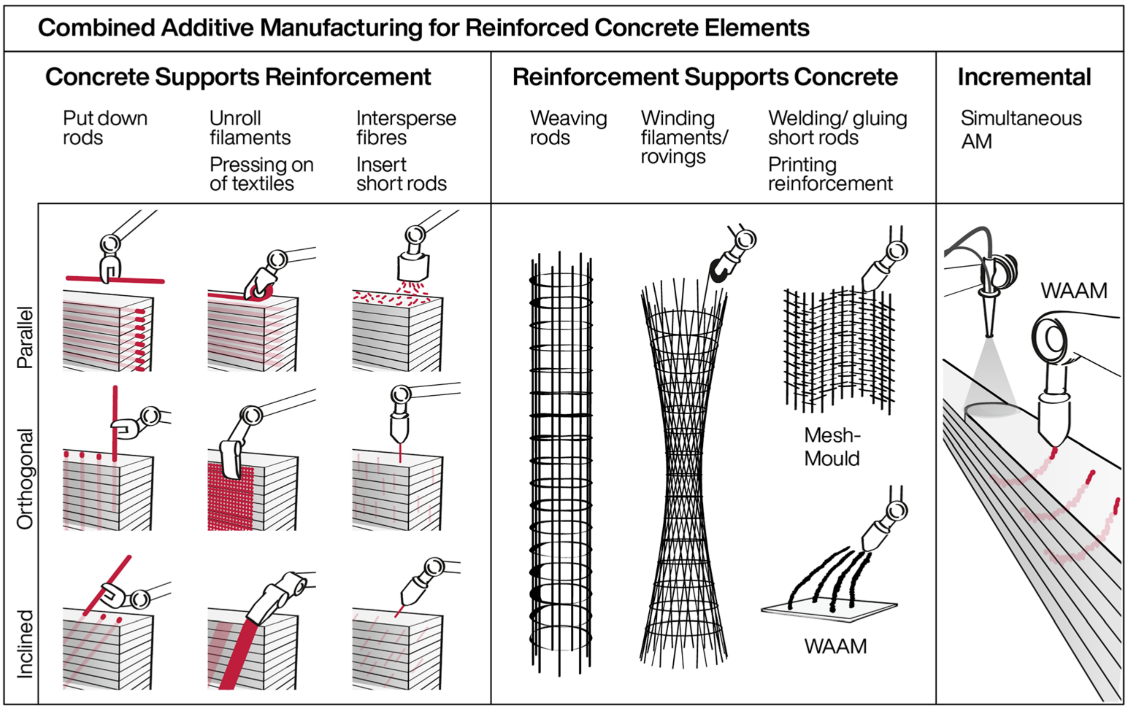


Figure 2.10 Stepwise schematic representation of combined additive manufacturing of TRC elements[69].

2.5 Hybrid yarn-based structure

Hybrid yarn combines distinct filament or yarn strands, resulting in synergistic characteristics. Thermoplastic hybrid yarns, used in thermoplastic composites, are flexible enough for textile preforming without significant damage [71]. These yarns consist of a high-performance reinforcing component and a thermoplastic matrix. Under heat and pressure, the thermoplastic fibres melt and penetrate the reinforcing filaments, forming a rigid composite upon cooling.

Thermoplastic polymers, with their higher viscosity compared to thermoset polymers, pose challenges for uniform and rapid resin impregnation. However, the homogeneous distribution of reinforcement and matrix reduces the mass transfer distance, leading to rapid and complete impregnation. This results in well-consolidated composite structures with low void content and superior mechanical properties.

Hybrid yarn can be produced using various methods such as co-wrapping, parallel winding, commingling, stretch-breaking (HELTRA process), air-jet texturing, KEMAFIL technology, Schappe technique, braiding, ring spinning, rotor spinning, wrap spinning, powder coating, and friction spinning. Combining multiple techniques can achieve optimal properties. Previous research has detailed these methods [71]–[73]. Here, a few hybrid yarn manufacturing methods are discussed for their feasibility in mass production and suitability for cement composite applications.

2.5.1 Commingled yarn

Commingled yarn is created by intermingling two or more filament bundle strands. The literature describes two methods for producing commingled yarn: using compressed air jets or employing an online commingling process.

2.5.1.1 Commingled yarn using compressed air jets

In the commingling process, compressed air is used to combine two or more yarn strands within a nozzle, creating inter-filament and intra-filament entanglements (Figure 2.11, a). One strand contains reinforcing filaments, while the other consists of matrix-forming thermoplastic filaments with minimal overfeed. The compressed air forms alternating open and compact sections in the yarn structure (Figure 2.11, b) [74]. The structure and properties of commingled yarn are influenced by process parameters and jet design.

Commingled yarn offers advantages such as filament-matrix homogeneity, reduced matrix mass transfer distance, improved impregnation, and faster processing during composite manufacturing. It is soft, flexible, and suitable for textile manufacturing. However, it can de-mingle during preforming processes like weaving, braiding, and knitting, leading to filament and matrix separation and the formation of resin-rich and resin-starved regions in composites, which hinders performance. Ensuring nip stability is crucial to prevent de-mingling and segregation of filament-matrix components [72], [75].

Alagirusamy et al. [74] found that increasing air pressure from 6 to 8 bar in a glass-PP commingled yarn structure increases nip length, interlacing degree, and nip frequency. High air pressure produces entanglement-type nip structures, while low air pressure results in braid-type nip structures.

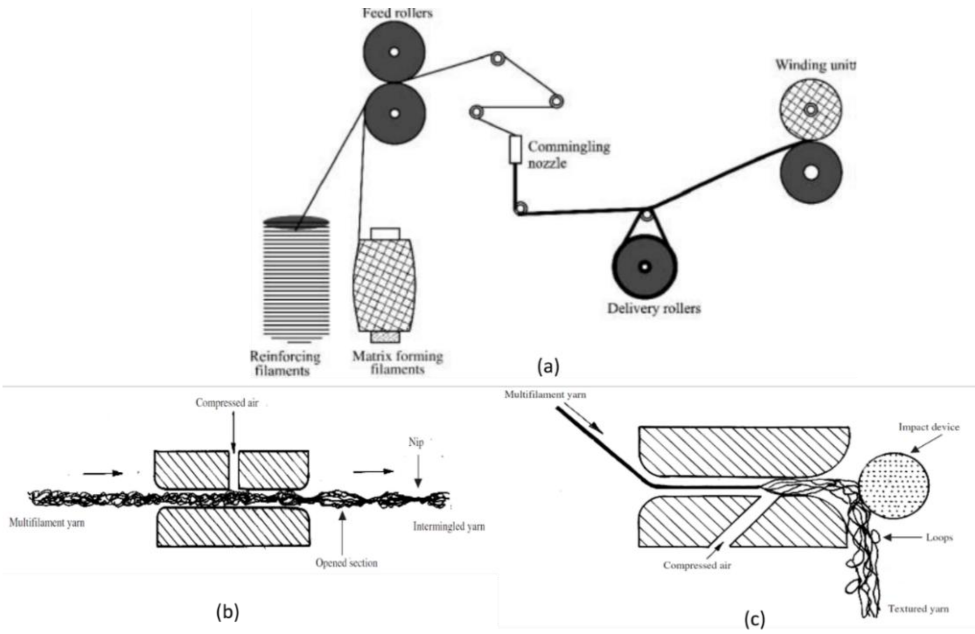


Figure 2.11 Schematic representation of: (a) commingling process for hybrid yarn production, (b) commingling nozzle action, and (c) air texturing nozzle action[72], [74].

Commingled yarns made of AR glass filaments and water-soluble polyvinyl alcohol (PVA) filaments in a 95:5 ratio enhance filament-matrix bonding when embedded in a cementitious matrix [27]. The PVA filaments dissolve, creating interstices that promote matrix penetration and improve the concrete matrix's microstructure by influencing the nucleation and crystallization of its mineral components. Despite being 30% weaker than AR glass roving, commingled yarns performed better in pull-out load tests.

TRC components made from commingled yarn-based biaxial warp-knitted fabrics showed 80% higher strength than those made from parent AR glass filaments. The mechanical behaviour of spread yarn, hybrid commingled yarn, and parent AR glass yarn was compared [28]. The pull-out load for spread yarn and commingled yarn was 300% and 80%

higher, respectively, than for the parent AR glass yarn bundle (Figure 2.12, a). Additionally, TRC components made from spread yarn and commingled yarn had tensile strengths 30% and 80% higher, respectively, than those made from parent AR glass-based warp-knitted fabric (Figure 2.12, b).

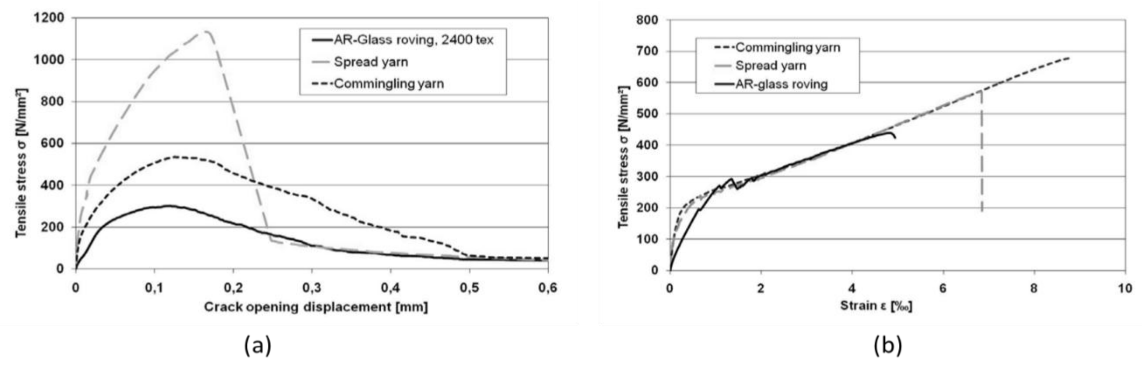


Figure 2.12 (a) Yarn pull-out behaviour for various yarn samples, (b) tensile behaviour of TRC specimens reinforced with different yarn samples[28].

2.5.1.2 Online commingling process

In online (in-situ) commingling, matrix and reinforcing filaments are simultaneously melt-extruded and combined (Figure 2.13) (Wiegand and Mäder 2017). This method offers benefits over traditional air-based commingling, such as minimal damage to reinforcing filaments, improved filament-matrix distribution, low mechanical stress, reduced void content, short melt flow distance for the matrix, better consolidation, and enhanced mechanical properties [76], [77]. Hybrid yarns suitable for thermoplastic composites through online commingling include Twintex® (Owens Corning), COMFIL® (ComfilApS), and Coats Synergex™ (Coats).

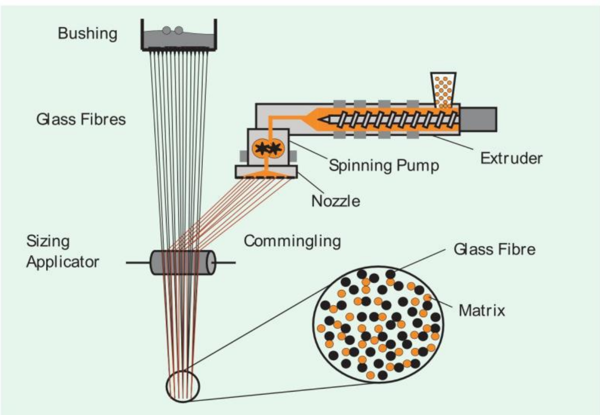


Figure 2.13. Schematic diagram of online commingled yarn formation with glass filaments as the reinforcing component and thermoplastic filaments as the matrix[77].

The mechanical properties of composites made with hybrid commingled yarn depend on sizing, size composition, and fibre-matrix volume content. Sizing improves the fibre-matrix interface. Pure silane sizing in the MA-g-PP matrix yields the highest strength and strain-to-failure results by forming covalent bonds between the glass fibre surface and the grafted matrix chains. For continuous real fibre processing, an additional film former is needed to ensure better strand integrity [77].

2.5.2 Air-jet textured yarn

Air jet texturing, similar to commingled yarn production, uses compressed air to combine reinforcing and matrix-forming filament strands. The process involves passing an air jet at a different angle and adding overfeed to facilitate loop formation in the yarn structure (Figure 2.11, c). Impact devices at the nozzle exit enhance yarn stability and quality [72]. Filament strands can be fed through the same rollers at the same speed (parallel end texturing) or through separate rollers at different speeds (core and effect texturing). Loop formation depends on the polymer type, filament denier, tensile properties, and filament cross-sectional shape [71].

However, like commingling, air jet texturing can result in resin-rich and resin-starved regions in composites due to loop opening and filament separation during textile preforming. The difference in modulus between reinforcing and matrix filaments causes variable load-bearing by the component filaments [78].

2.5.3 Powder coated yarn

In the powder coating process, reinforcing filaments (tows) are drawn from the package and spread out in a pneumatic spreader. They undergo pre-heating in a convection oven, pass through a vibrating bath of powder polymer, and are then consolidated in a convection oven. Finally, the towpregs are cooled and wound onto a package [79]. Figure 2.14 illustrates this process. Towflex® (Hexcel Composites, Stamford, CT) is a commercially available powder-coated reinforcement yarn made from carbon, glass, or aramid fibres impregnated with PP, PA, PPS, PEI, or PEEK.

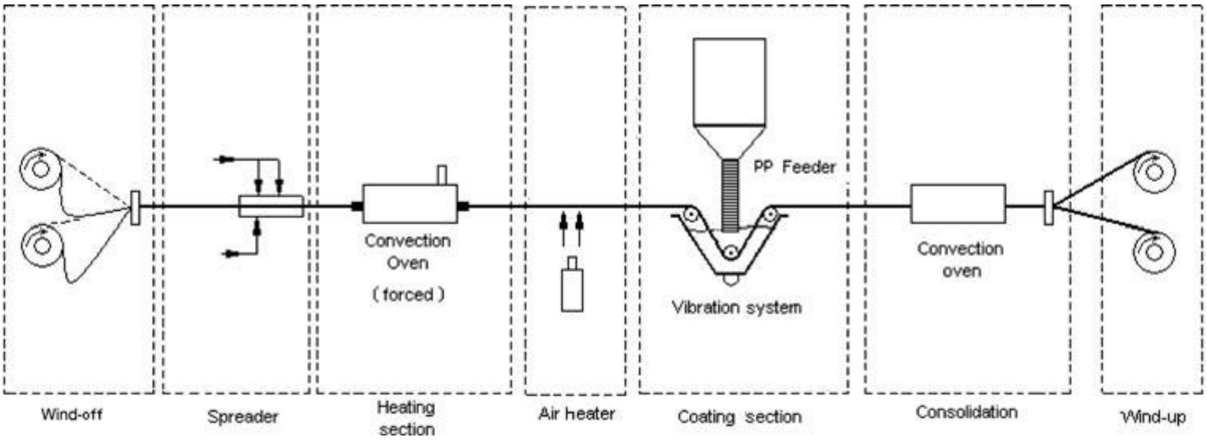


Figure 2.14. Powder coating setup for towpreg production[79].

An electrostatic powder coating setup for flexible thermoplastic towpregs uses electrostatic, aerodynamic, and gravitational forces for impregnation. Key parameters such as voltage, air pressure, fluidization pressure, tow speed, and gun distance affect the coating's effectiveness and uniformity [80]. Research shows that tow speed significantly influences fibre volume fraction in polypropylene-coated carbon tows [81].

Unidirectional carbon-polypropylene composites produced via powder coating exhibit 19% and 68% higher flexural strength than those produced by DREF friction spinning and film stacking methods, respectively, due to uniform resin coating and higher impregnation of carbon tows. Powder coating is highly effective for producing thermoplastic composites from polymers with both low and high melt viscosities [82].

2.5.4 Cable yarn

Cable yarn is made by wrapping a surface filament strand uniformly and spirally around a core filament strand without twisting the individual strands [38]. This principle is also used in hollow spindle spinning, wrap spinning, and co-wrapping. The core filament provides strength, while the surface filament protects the core from abrasion and creates a ribbed texture for better mechanical anchorage in TRC. Figure 2.15 (a) shows the cabling process: the core strand passes through a hollow tube, and the cover yarn is wrapped around it using a cabler spindle pot to form cable yarn (Figure 2.15, b). Repeating the process with spindle rotation in the opposite direction creates cable yarn with a cross-wise running cover yarn (Figure 2.15, c) [20].

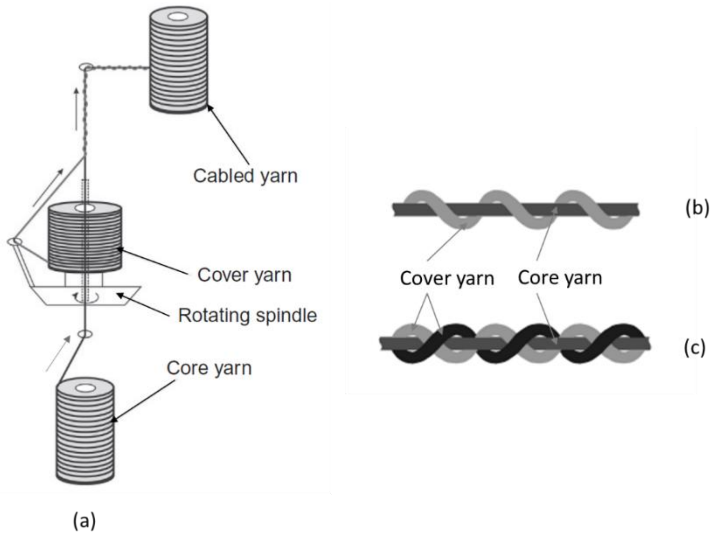


Figure 2.15 Schematic representation illustrating: (a) cabling process for creating core-sheath wrapped hybrid yarn structure, (b) cable yarn with single-sided wrap, (c) cable yarn with double-sided wrap[20], [38].

2.5.5 DREF spun core-sheath yarn

The DREF friction spinning system, invented by Dr. Ernst Fehrer, produces core-sheath yarn structures. Figure 2.16 shows the DREF-III process for hybrid yarn production, where fibres are drafted and individualized using a rotating saw-tooth carding roller. These fibres then interact with a continuous filament strand on a rotating perforated friction drum, forming the yarn through frictional contact. The resulting DREF yarn features a sheath of staple fibres uniformly covering the central filament strand. These sheath fibres enhance inter-filament binding and prevent slippage and abrasion during processing. DREF spun yarn can create profile strands by partially melting thermoplastic sheath fibres (e.g., PP, PET, PA), improving yarn surface area and fibre-matrix bonding [20]. Benefits of DREF spun yarn include a twist-free core, high reinforcing efficiency, and abrasion protection [37]. Adhesion issues between sheath fibres and core filaments can be mitigated with controlled heat treatment [23], [37].

A study by Bar et al. [37] compared DREF yarn composites with conventional film stacking composites, using flax yarn as reinforcement and polypropylene as a matrix. DREF yarn composites outperformed the film stacking composites in terms of tensile strength, flexural strength, impact strength, and flexural modulus. They showed lower void content, uniform fibre-matrix distribution, and shorter resin flow distance, contributing to improved mechanical properties.

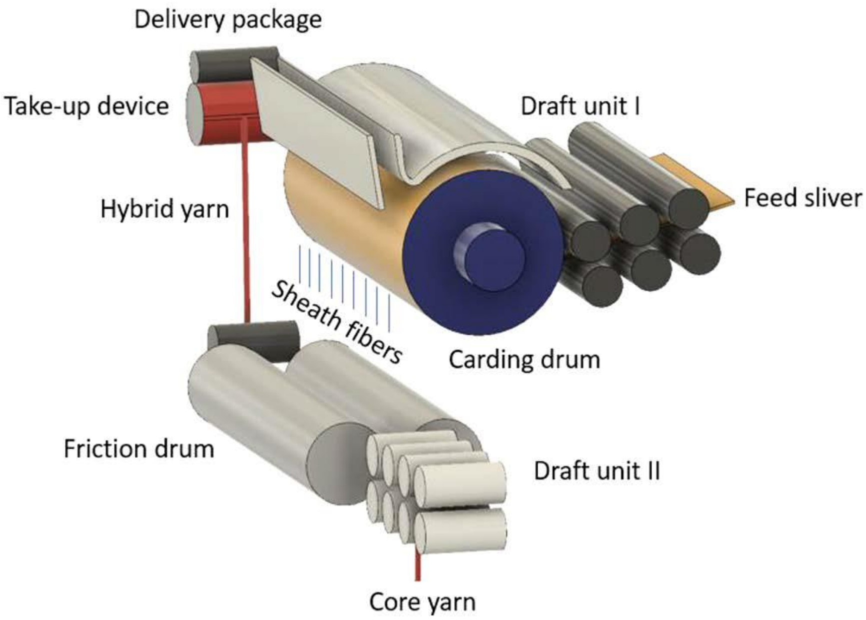


Figure 2.16. DREF III spinning process for producing core-sheath yarn structure[83].

DREF spinning offers several advantages compared to other hybrid yarn manufacturing methods [84]:

- It requires less power compared to ring spinning because it does not rotate the final yarn package.
- It achieves a high production rate.
- It does not twist the core of the yarn structure.
- It can produce coarse yarns over a wide range of counts.
- The ratio of fibre core to sheath content can be adjusted as needed.
- It can utilize drawn sliver for yarn production.

The DREF spinning system is highly effective for producing core-sheath hybrid yarns, combining reinforcing fibres in the core with thermoplastic staple fibres as the matrix. The DREF-3 spinning machine is found suitable to develop hybrid yarns using glass, carbon, or aramid filaments. While DREF spun yarns show great potential for composite reinforcement, they are unsuitable as warp threads in woven textile preforms. During weaving, the sheath components can disengage from the yarn structure due to weaving forces, leading to frequent thread breaks and limiting their use as composite reinforcements [36], [84].

2.5.6 Braided structure

In traditional braiding machines, yarn carriers move in circular paths, with half moving clockwise and the others counterclockwise, creating 2-dimensional tubular and flat braids. These machines, also known as Maypole-type machines due to their serpentine or maypole carrier path, produce preforms vertically or horizontally. Rotary braiders employ two rotating tables [85]. The braiding angle, crucial for the geometry of the preform, typically ranges from 30° to 80° relative to the longitudinal direction (braid axis) of the preform and the deposited yarn strand [86].

Braiding is a key method for producing hybrid yarns, exemplified by the core-sheath structured micro-braided hybrid yarn shown in Figure 2.17. A braid consists of interlacing three or more textile or flexible strands at an angle (± θ°), sometimes with an axial thread placed at 0° to the braid axis. Vertical braiding is more popular due to its space efficiency compared to horizontal braiding. Braid structure features are influenced by factors such as mandrel diameter, take-up speed, and bobbin rotation speed [87], [88]. Braided structures offer high conformability and damage resistance, making them ideal for structural applications in industries like aerospace, automotive, and defence [84], [89].

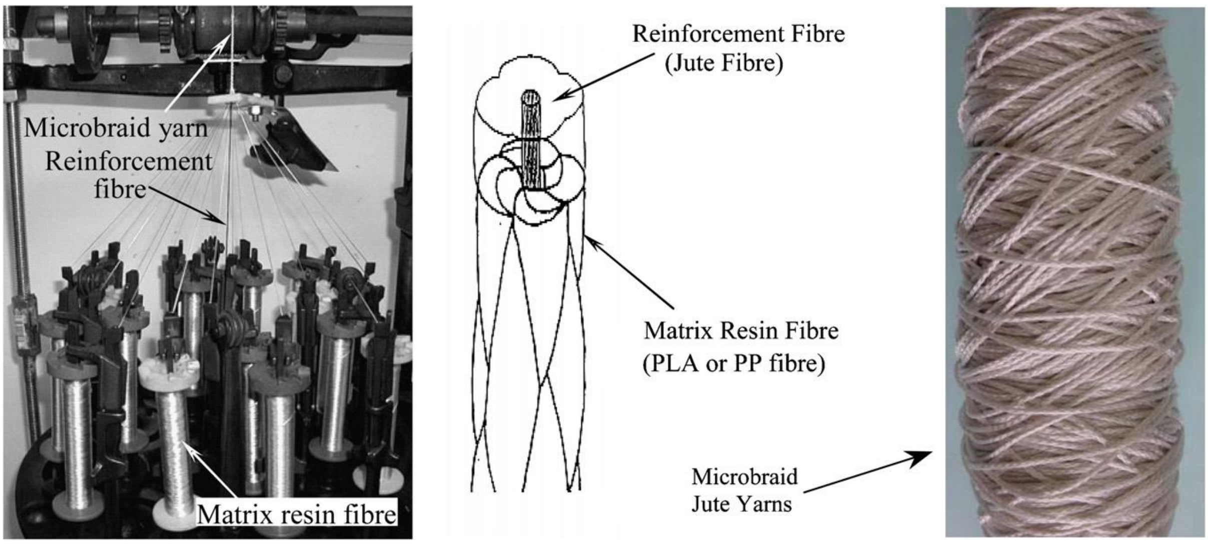


Figure 2.17 Production of micro-braid yarn (MBY) featuring a jute fibre core and a thermoplastic fibre (PP/PLA) sheath using a 16-spindle braiding machine[90].

In Jute/PLA microbraid composites, increasing the fibre volume fraction enhanced both maximum tensile stress and modulus. Optimal processing conditions were identified at higher pressures (2.7 MPa) and temperatures (175°C) for fabricating these composites.

Introduction of Jute fibres into PP microbraid composites significantly improved the tensile and bending properties compared to pure PP. Micro-braiding improves matrix fusion, resin wetting of fibre bundles, interfacial adhesion, and reduces fibre attrition and associated strength losses seen in other processes like injection moulding. The high viscosity of molten thermoplastic polypropylene poses challenges for impregnating reinforcing fibre bundles, necessitating thorough study of processing conditions to optimize fibre/matrix interfacial properties in micro-braiding [90].

The flexural performance of hybrid braided structure reinforced concrete was compared with specimens using uncoated and epoxy-coated AR glass yarn, uncoated carbon yarn, and epoxy-coated carbon yarn [32]. The hybrid structure, comprising AR glass roving core and polypropylene yarn sheath, increased flexural strength by 57.71% compared to plain concrete. While epoxy-coated variants exhibited superior flexural behaviour in TRC, the cost and complexity of epoxy coating should be noted. Carbon reinforcement showed the highest flexural strength at 40.8 MPa among all tested variants.

Hybrid braided structures were developed using basalt, AR glass, and carbon roving fibres with polypropylene filaments [33]. Carbon-based structures showed the highest flexural strength, followed by AR glass, while basalt structures exhibited the lowest. Reinforcement significantly improved flexural behaviour compared to unreinforced specimens, with closer textile reinforcement depths (3, 5, and 10 mm from the bottom face) contributing to higher strength. For instance, carbon hybrid yarn enhanced strength 3.3 times at 3 mm, 2.6 times at 5 mm, and 1.8 times at 10 mm compared to unreinforced concrete. Different textile structures (grid sizes 10 mm x 10 mm, 10 mm x 50 mm) influenced flexural behaviour, with the 10 mm x 50 mm structure offering better concrete penetration and higher contribution to strength. Reinforced samples displayed ductile behaviour with significant deformations before failure, beneficial for earthquake-resistant design. Compared to flexural strength, hybrid structures increased energy absorption, particularly evident in basalt hybrids, enhancing both strength and energy absorption at varying depths.

2.6 2-D woven fabric

To produce woven fabrics, weaving operations are carried out on a loom. Weaving involves the interlacing of warp (the yarn that runs lengthwise along the machine) and weft (the yarn that runs across the machine) at right angles. The term "weave" refers to how the warp and weft threads intertwine with each other. The most frequently used weave patterns include plain, twill, satin, sateen, leno, gauge, and triaxial (Figure 2.18).

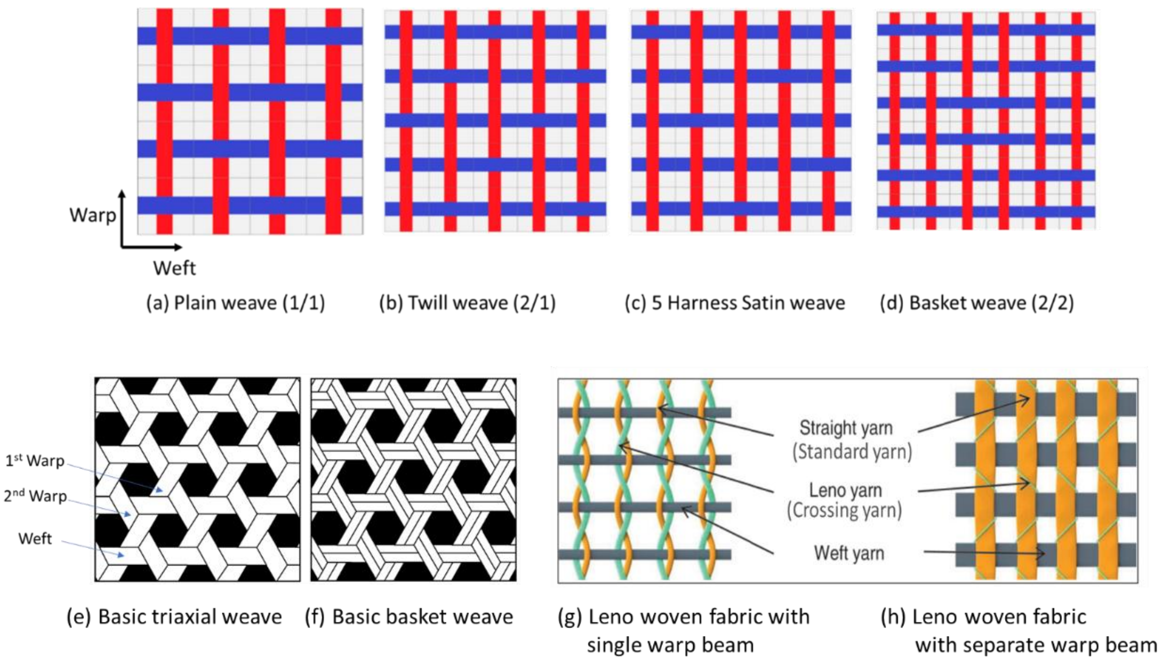


Figure 2.18 Representation of basic 2-D woven structures used for FRCM reinforcement[91]–[93].

In woven fabric, warp and weft yarns are held together by friction in the interlacement regions. Yarn crimp from weaving impacts fabric mechanics in cement composites. Dense weaving limits mortar penetration, weakening the mortar-fabric bond. Open or scrim, triaxial, and leno weaves are preferred for better reinforcement structure and mortar penetration [22].

2.7 2-D woven fabric based FRCM

The weaving process induces crimp in the fabric structure, resulting in underutilization of the reinforcement potential of filament yarn. Crimped geometry in woven structures may reduce reinforcement efficiency, and stress concentrations in the matrix may occur due to yarn curvature [14]. However, the special curvature present in the structure improves mechanical anchorage with the cementitious matrix, especially for synthetic yarns [94]. Improvements in pull-out load and flexural behaviour have been reported for woven fabric reinforced cementitious composites due to the special crimped geometry of woven fabrics [12], [94]. The fabric parameters should be optimized to achieve the desired mechanical properties of woven TRC, which are determined by the yarn diameter, number of ends/unit length, number of picks/unit length, and fabric construction [12]. The flexural behaviour of fabric-reinforced cementitious composites depends on two factors: reinforcement content (volume fraction) and cementitious matrix penetration into the fabric structure. Optimizing these factors enhances flexural properties, including higher load capacity, toughness, multiple cracking, and greater ductility [95], [96].

2.7.1 Fibre type

TRC reinforced with carbon, AR glass, and polyethylene (PE) was dynamically tested at 0.25 m/s. Carbon fabric has superior tensile and ductility properties in both fabric and cement composite forms. The carbon fabric's reinforcing efficiency is not fully utilized due to multifilament yarn and insufficient matrix penetration in the yarn bundle, resulting in multiple cracking and fibre pull-out behaviour in carbon TRC. In contrast, AR glass TRC exhibited effective stress transfer without fibre slippage, as the fibres were bonded by size. No such failure behaviour was observed in PE TRC [97].

Glass fabric reinforced concrete slabs show higher displacement, better residual capacity, and less scabbing than basalt textile reinforced concrete slabs under impact loading [98].

2.7.2 Reinforcement ratio and number of fabric layers

Increasing the number of fabric layers and using coarser yarns in concrete specimens increases the reinforcement ratio, resulting in improved flexural behaviour such as higher load bearing ability, strain hardening behaviour, and ductility [99]. For example, low modulus nylon fabric reinforced concrete specimens with 430 tex yarn and 1.15% reinforcement ratio showed strain-hardening behaviour under flexural loading [100]. Ductile failure with multiple crack formation occurs in specimens with an increased number of fabric layers under flexural loading [99], [100]. Four-layer carbon fabric reinforced RC slab showed 3.5 times higher load-bearing capacity than un-strengthened RC slab. Fabric-enhanced slab specimens exhibited finer, smoother, and smaller crack patterns, compared to the large cracks seen in un-strengthened RC slabs. Increasing the number of fabric layers resulted in a more distributed crack pattern with smaller crack spacings [101].

The impact strength of AR glass reinforced cement composites was higher for six layers (V_f 2.7%) than for two layers (V_f 0.9%), with strengths of 29.8 and 11.5 MPa, respectively. PE fabric had good impact performance compared to carbon and AR glass, and could withstand higher impact loads with minimal damage and no composite failure. To improve impact performance, reinforcing the tension side (bottom face) of cement-composite specimens is recommended. Another study found that the impact resistance of basalt fabric reinforced concrete slabs decreased with increasing number of layers due to delamination and crack formation. The optimal number of layers for both glass and basalt fabric were five, with insignificant improvement beyond this number. Basalt demonstrated better post-peak impact response than glass reinforced TRC, and increasing the number of layers improved residual capacity in both cases. Furthermore, repeated impact loading resulted in minimal scabbing and no fragmentation of both basalt and glass TRC specimens [98].

2.7.3 Embedment length

A plain-woven fabric with polyethylene monofilament yarn and varying picks/unit lengths was subjected to a pull-out test at a speed of 0.25 mm/s. The effect of embedded length on the pull-out load was investigated using three different lengths (10, 15, and 20 mm), and it was found that the 20 mm embedded length provided the highest pull-out load due to greater depth of yarn and fabric embedded in the concrete. Crimp yarn and fabric outperformed straight yarn due to their crimp structure and mechanical anchorage [12].

2.7.4 Yarn twisted configuration

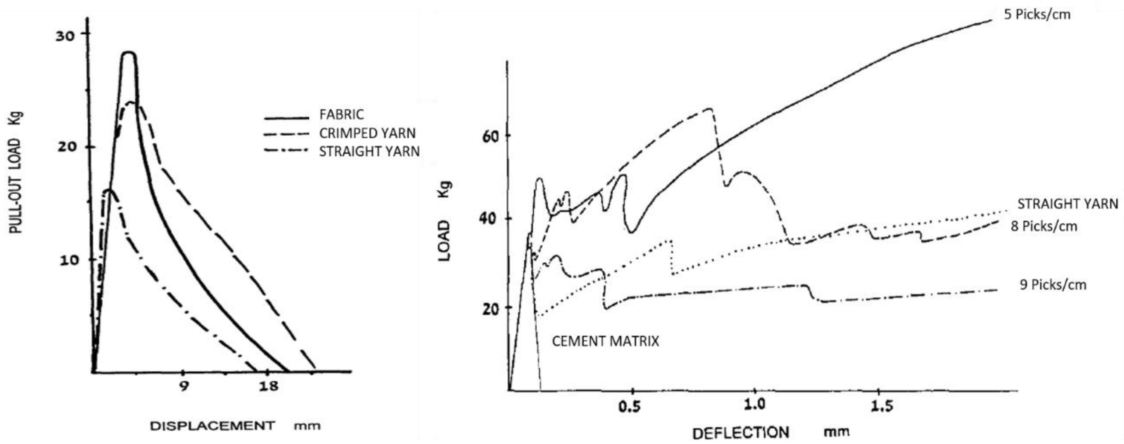
For strain hardening in concrete specimens, twisted yarns need higher reinforcement ratios than untwisted ones. Although twisting can enhance bond behaviour, its reinforcing efficacy decreases. Nylon yarns used in reinforced concrete shrink by 2-3% in alkaline cement pore solutions, leading to post-tension stress in the concrete. As a result, the uncracked zone in reinforced concrete exhibits greater strength than unreinforced concrete [99].

2.7.5 Yarn fineness

Fabrics with yarn fineness of 213 tex and 430 tex have similar flexural strength at lower reinforcement ratios (one layer). However, increasing the reinforcement ratio has a greater impact on flexural strength, and thicker yarns improve the flexural behaviour of fabric-reinforced concrete specimens. In addition, using 430 tex yarns instead of 213 tex improves the flexural behaviour of concrete specimens, including load capacity, strain hardening behaviour, and crack pattern. Coarse yarns also have better bonding and higher pull-out load in concrete [99], [100].

2.7.6 Yarn geometry and pick density

The wave length and amplitude of the weft and warp yarns are influenced by fabric density, which in turn affects the fabric-matrix bonding in cement composites [102].The bond strength between the fabric and matrix is enhanced by increasing weft density and yarn crimp curvature, resulting in better composite performance. However, the flexural properties of fabric composites are inferior to those of crimped untied yarn composites due to reduced penetration of the cementitious matrix inside the fabric structure, which is more pronounced in fabrics with higher weft densities. In cement composites, reinforcement using fabric and crimp yarn removed from the fabric showed superior performance in comparison to straight yarn. This may be due to the mechanical anchorage provided by the crimp geometry of the yarn, particularly in the case of fabric and crimp yarn removed from the fabric, as shown in Figure 2.19 (a). It was reported that, fabric reinforced cement composite with a weft density of 5 yarn/cm exhibited a higher pull-out load compared to those with 8 yarn/cm and 9 yarn/cm, indicating improved cement matrix penetration due to the fabric structure, as shown in Figure 2.19 (b) [12].



(a) Effect of yarn and fabric geometry (b) Effect of pick density in fabric

Figure 2.19Pull-out load-displacement graphs: (a) performance of fabric, crimped yarn removed from a fabric and a straight yarn embedded 20 cm in a cement composite, and (b) behaviour of a cement matrix reinforced with polyethylene fabric and variable picks per unit length (pick density), as well as a straight yarn reinforced in cement composite under pull-out loading[12].

The microstructural view of cement composites with varying weft densities shows that a lower weft density of 5 yarn/cm has denser cement penetration and no defects compared to a higher density of 10 yarn/cm, which exhibits lower matrix penetration and the presence of voids, as shown in Figure 2.20 [94]. To improve the compaction and flexural behaviour of cementitious composites, the authors propose modifications to the manufacturing process [94].

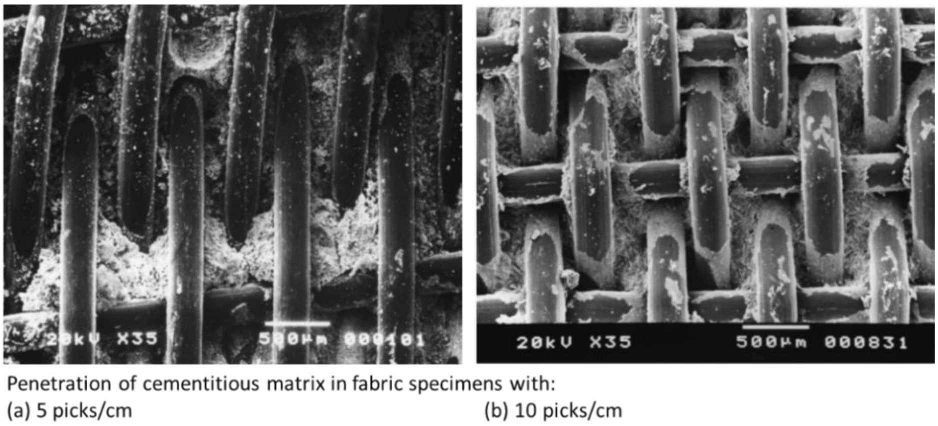


Figure 2.20SEM microstructure images depict cement composite reinforced with polyethylene monofilament woven fabrics of varying picks density: a. 5 picks/cm, and b. 10 picks/cm[94].

The AR glass leno fabric had a fixed warp density but different weft spacings (10, 20, 30, and 50 mm). Fabrics with a small weft spacing of 10 mm were prone to weft defects, resulting in the lowest first cracking strength of 3 MPa. Increasing the weft spacing led to tension stiffening, with the first cracking strength reaching around 7 MPa. The stiffness of the multi-cracking zone was higher for weft spacings of 30 mm and 50 mm, as the longer bond length prevented longitudinal delamination. The specimens with 10 mm weft spacing had higher ultimate strain due to the presence of longitudinal cracks, allowing the roving to stretch. The peak load was similar for all weft spacing configurations, with only tension stiffening being affected, not the efficiency factor value [61].

2.7.8 Fabric grid opening size

As the mesh size of fabric specimens decreased from 10 mm x 10 mm to 5 mm x 5 mm while keeping yarn fineness constant, the number of reinforcing yarns and reinforcement ratio increased. This led to better performance under flexural loading, with higher flexural load, greater ductility, and strain hardening behaviour observed in the fabric specimens with a mesh size of 5 mm x 5 mm. Small mesh sizes resulted in higher flexural load and ductile behaviour, as evidenced by multiple cracks with small crack width [99].

The fabric specimen with a 2 mm mesh size showed the highest flexural load due to strain hardening behaviour and multiple cracking. However, with increasing mesh size, the volume fraction of the fabric decreases, leading to pseudo deflection hardening behaviour for mesh sizes between 2 mm and 10 mm and strain softening behaviour for 20 mm mesh size. A fabric specimen with 0 mm mesh size exhibited poor filament-matrix bonding, resulting in lower flexural load despite having the highest volume fraction. SEM analysis revealed that increasing mesh size allows for free water flow and better fibre-matrix bonding. For specimens with a larger mesh size, lower flexural behaviour is associated with lower reinforcement content. Maintaining a volume fraction between 0.19% and 1.34% increases toughness by 5.6 to 52-fold compared to unreinforced specimens.

Further, fabrics with varying mesh sizes of 2, 4, 6, 8, and 10 mm were created with a similar weight (approx. 15g) and volume fraction (0.6-0.7) by combining multiple carbon yarns. All specimens showed similar curves with strain hardening behaviour, indicating that mesh size does not independently influence the flexural behaviour of reinforced cementitious composites. The filaments' interaction with the matrix determined the flexural strength and toughness of the specimens. The specimen with 2 mm mesh size had significantly higher flexural toughness and toughness indices at the post-cracking point than the others, suggesting that fabric volume fraction significantly influences composite flexural properties. Increasing fabric mesh size at a constant textile volume content reduces the sample toughness indices [95].

The impact behaviour is affected by the grid size or fabric openness, where open AR glass fabric leads to multiple cracking without complete specimen failure due to improved mechanical anchorage of filaments-matrix provided by better cement matrix penetration into the fabric structure. However, the closely packed AR glass fabric structure causes a reduction in impact strength after specimen failure [103].

2.7.9 Fabric weave design

Twill fabric structure has fewer interlacing points, resulting in lower tensile strength and slightly lower limit of proportionality (LOP) values under flexural loading compared to plain fabric structure. Modulus of rupture (MOR) values were significantly higher in concrete reinforced with plain and twill fabric structures with higher thread density due to an increase in the number of warp yarns in the load direction, contributing to higher flexural load. The weave design has no significant effect on MOR values as the warp yarn has already de-crimped under tensile load at higher bending loads. Weft yarns perpendicular to the loading direction can affect bending load. The impact of weave design on toughness characteristics is less noticeable at higher bending deflection due to warp yarn de-crimping effect. During bending deflections of composites, tensile behaviour of warp yarn is crucial [30]. The plain weave pattern is widely utilized in TRC owing to its exceptional stiffness and strength. The twill weave pattern is better suited for applications that require high deformability, whereas the satin weave pattern offers superior flexibility and drapeability. In TRC, the leno weave pattern is preferred for forming open scrim fabric, which enables ease of matrix flow and penetration within the interstices of the fabric.

2.7.10 Hybrid fabric

Hybrid fabric structure is similar to hybrid yarn structure in that it combines different materials to achieve synergistic performance. This can be achieved through (a) using reinforcement of two or more fabric layers made of different materials in concrete, or (b) using a single fabric made of different yarns in different orientations. Hybridisation allows for the combination of low-cost, low-modulus yarns (such as PP, PE, and PET) with high-cost, high-modulus yarns (such as carbon, aramid, basalt, and AR glass) to achieve excellent mechanical properties at a reasonable cost.

The type of fabric used affects the impact behaviour of TRC slabs, with glass fabric showing the least damage due to high energy absorption, followed by basalt fabric. Hybrid TRC showed larger spalling and local failure. However, combining basalt and glass (hybrid fabric) showed the highest impact resistance, absorbing more energy at lower levels (50 J). Mid span deflection was lowest for hybrid textiles at higher energy levels (100 J and 200 J). Full factorial analysis showed significant interaction between fabric type and energy levels for all TRC types [31].

Carbon-polypropylene hybrid woven fabric reinforced concrete beams exhibit flexural toughness 6.5-40.75 times higher than that of unreinforced concrete beams [30].

2.8 Non-crimp fabrics for TRC reinforcement

Non-crimp fabrics (NCFs) are textile assemblies formed by single or multiple layers of straight roving/yarn without interlacement and arranged onto one another in different possible orientations (0°, 90°, +45°, -45°), held together by stitching thread to form a single fabric [23] (Figure 2.21). The main objective of NCF is to form a structure without crimp which is expected to yield best possible mechanical properties in composites. Multi-axial warp knitting process is commonly employed to produce NCF which has found applications in different sectors such as aircrafts, automobile, geotextiles and construction. However, stitching process has some limitation as it causes damage to filaments which result in loss of strength. It also leads to poor impregnation of coating inside the roving bundle. [104], [105]. In another study, NCF was produced in form of bi-axial warp knitted fabric (open grid structure) with pillar stitches. The warp roving cross-section was circular because of the lateral forces imposed by pillar stitches. However, weft roving has a flat and elliptical cross-section. There was no visible effect of knitting tension on roving cross-section in all stitch length. It was found that, stitch length is an important parameter which influences the roving cross-section and fibre packing density and fabric properties. Shorter stitch length does not allow roving flattening and provide dense packing of fibres in roving structure of warp and weft. [106]. An attempt was made by Al-Monsur et al. to produce "stitch-free NCF" bonded by adhesives. Two different types of adhesives were considered – reactive adhesives and hot melt adhesive binder. The bond strength, drop mass and curing duration of adhesives was studied for glass and carbon roving. Hot melt adhesives offered minimum drop mass of adhesives which led to shorter curing duration. It was observed that fibre sizing and selection of adhesive has a greater influence on bond strength. The higher drop mass and lower viscosity of reactive adhesives has resulted in improved penetration of adhesives inside the roving bundle. Hence, bond strength offered by reactive adhesives was higher and better compared to hot melt adhesives [104].

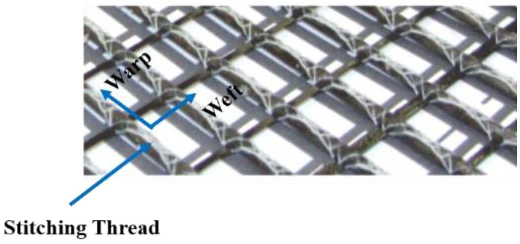


Figure 2.21 Non-crimp fabric (NCFs) for concrete reinforcement with warp (50K Carbon Roving) and weft (12K Carbon Roving) held together by stitching threads[105].

2.9 Methods of improving fibre-concrete bonding

2.9.1 Surface modification of FRP rods

Pull-out resistance is crucial for reinforcement in concrete, as it prevents slippage. The pull-out behaviour of reinforcing yarns within a cementitious matrix depends on the interface between the yarn and the matrix. Achieving higher pull-out resistance enhances the bond and avoids slippage. Surface roughness or ribbed structures in FRP rods significantly improve bonding through mechanical anchorage with the cementitious matrix. Similarly, steel bars have ribs to enhance bonding. Methods such as sand-epoxy coating, filament wrapping, milling, and braiding are used to improve the bond between reinforcement and matrix [43].

Sand-epoxy coating involves coating FRP rods with epoxy resin and uniformly distributing fine sand particles over them. Figure 2.22 illustrates methods for creating different geometric profiles in carbon FRP bars. In the additive method, a roving or tape is wrapped around the FRP bar or sanded. In the subtractive method, drilling or milling generates desired profiles.

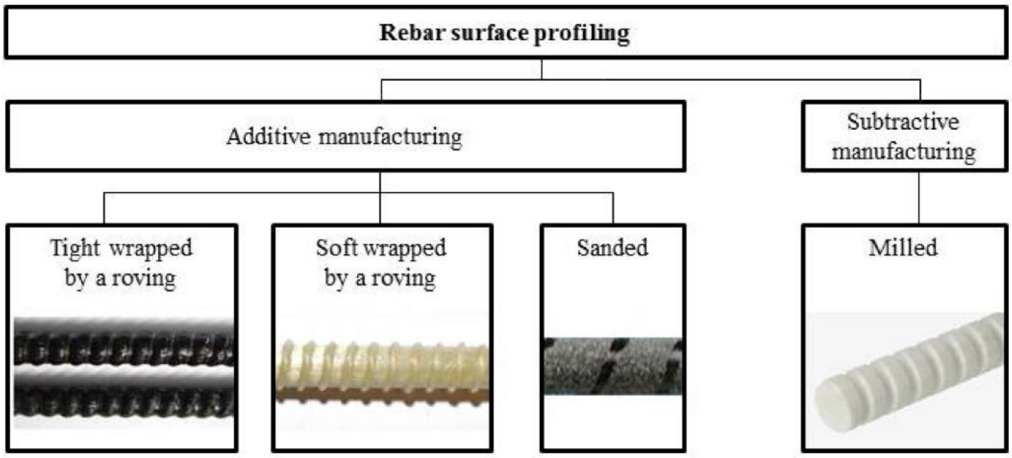


Figure 2.22 Different profiling methods used in FRP bars to improve bonding behaviour in concrete[107].

2.9.2 Modified braided rod structure

Compared to pultruded rods, braided structures offer advantages like multiaxial orientation, better damage tolerance, improved mechanical properties, and the ability to produce deformed rebars for enhanced FRP-concrete bonding. Braided FRP rebars provide higher flexural and shear strength, increased durability, and improved crack resistance, making them ideal for civil engineering applications. Despite higher costs, braiding offers significant benefits, particularly in applications needing extra ductility and enhanced bonding [22]. Research confirms the effectiveness of the braiding process in creating structural composite rods for concrete reinforcement [108]–[110]. Hybrid braided structures enhance the flexural and shear strength of concrete and are useful in sensing and health monitoring [32], [33], [111]–[115]. Pultruded hybrid core-sheath rods demonstrate high interface shear strength and fatigue resistance, making them potential steel rod substitutes in underground oil extraction [116]–[118].

Braiding process naturally creates a non-uniform surface, which enhances bonding. Modifying the braiding process by using coarser yarn (rib yarn) forms prominent rib profiles, as shown in Figure 2.23. The hybrid braided structure combines a resilient Kevlar 49 aramid filament sleeve with a high modulus carbon filament core for initial deformation resistance. Produced on a 24-carrier braiding machine, it uses 3-ply 1,240 denier Kevlar 49 yarns and a 15-ply 1,240 denier Kevlar 49 rib yarn for mechanical adhesion to concrete (Figure 2.23, a-b). The 3 mm bar features regular modulus carbon (T300) and Kevlar 49 fibres with a vinylester matrix, while the 5 mm and 10 mm bars use high modulus carbon (Thornel P-55S) and Kevlar 49 fibres with an Epon 828 epoxy matrix. The braided structure is transformed into composite bars via a combined braiding and pultrusion process (braidtrusion) [119]. The ductile hybrid FRP (D-H-FRP) enhances concrete bond strength through rib yarn braiding for mechanical anchorage (Figure 2.23, c-d). Rib height and spacing can be adjusted for desired adhesion. The D-H-FRP bar provides strong initial tensile resistance and a gradual failure process, showing a distinct post-yield slope decline in the stress-strain curve before achieving high ultimate strain levels [120], [121].

Moon et al. [122]enhanced GFRP rebar surfaces to improve bond behaviour with concrete by creating three types: sand-coated (SCR), deformed (DR), and surface-braided (SBR). SCR and SBR have rough particles and fibres, while DR features ribbed surfaces from milled glass fibres and epoxy resin. Won et al. [123] developed three hybrid braided FRP rebars: Rebar A with a carbon core and aramid sleeve (27/73), Rebar B with a carbon core and glass sleeve (19/81), and Rebar C with a carbon core and aramid-glass sleeve (13.6/34.6/51.8). Rebars A and C exhibit over 3.4% pseudoplastic deformation, enhancing structural safety under dynamic loads like earthquakes or wind, a feat not achieved by existing FRP reinforcements. Aramid sleeves fail with brittle fractures, while glass braids fail with necking. Hybrid FRP rebars show elastic behaviour until early fracture, with irregular sleeve breakage and regular core fracture patterns.

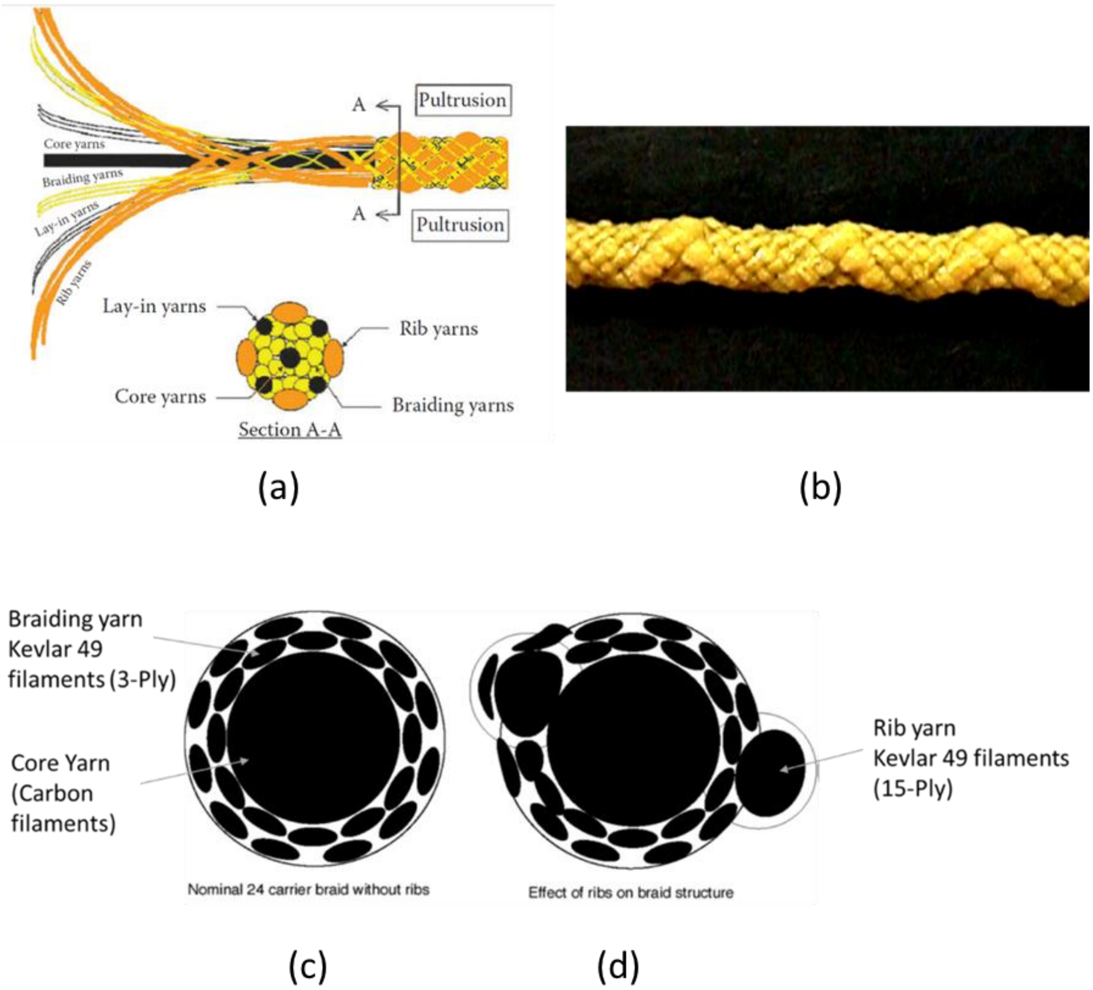


Figure 2.23 (a) Schematic representation of the constituents in a hybrid Carbon-Kevlar 49 braid structure, (b) micrograph of the hybrid Carbon-Kevlar 49 braid structure showing surface rib yarn, (c) schematic representation of a hybrid braid structure with a carbon core and Kevlar 49 sheath, and (d) schematic representation of a modified hybrid braid structure with coarse Kevlar 49 rib yarn [119], [121].

2.10 Coating textiles

Coating applications significantly impact the properties and durability of TRC and are categorized into yarn/roving and fabric coatings. These coatings should evenly cover fibres, resist alkaline ions, facilitate fabric formation, and prevent filament damage while remaining flexible under bending forces. High-performance tows have numerous filaments, making individual activation impractical. The filament-matrix bond is crucial for strength utilization and load transfer in concrete. Uncoated specimens exhibit weak bonding, resulting in poor interface and pull-out behaviour [22].

The textile coating on TRC serves several key functions:

1. Enhances Bonding: Promotes bonding between filaments and cementitious matrices, ensuring optimal load transfer and reinforcement utilization.
2. Prevents Filament Damage: Protects filaments from friction damage during fabric production.
3. Improves Adhesion: Enhances adhesion between the concrete matrix and reinforcing fibres, boosting fibre-matrix bond performance [105].
4. Enhances Structural Stability: Contributes to fabric structure stability and facilitates easy handling during concreting [105].
5. Provides Protection: Acts as a protective layer, shielding filaments from the highly alkaline pore solution of the cementitious matrix, crucial for alkali-sensitive materials like glass filaments [105].

These functions collectively enhance the performance and durability of textile-reinforced concrete structures.Effective matrix and composite consolidation are crucial for alkali-sensitive filaments such as glass filaments. While coating textiles enhances strength and durability, it also increases material and processing costs. Thermoset resin coatings, in particular, can reduce flexibility, which may lead to crack propagation during handling and use [124].

2.10.1 Coating of filament bundle

An uncoated multifilament roving strand comprises two filament types: outer filaments, which are directly connected to the concrete matrix, and inner filaments, whose bond properties are determined by friction since they lack direct interaction with the matrix [19]. Unlike traditional reinforced concrete, where mechanical anchorage between rebar ribs and the concrete matrix is key, fabric rovings rely on adhesion and friction due to their relatively smooth surface. To improve surface roughness and bond performance, sand-coated surface rovings (SCS) were developed [125]. Pull-out tests on three types of carbon rovings – uncoated, SBR-coated, and SCS-coated—revealed that roving surface coating significantly affects the roving-matrix interface properties. The bond-slip behaviour typically shows an initial linear increase in bond stress (zone I) until peak bond stress is reached, followed by a softening response (zone II) with decreasing bond stress, and finally, a frictional bond stress (zone III) at about 15-30% of the peak bond stress. SCS rovings demonstrated higher peak bond strength compared to SBR-coated and uncoated rovings. Uncoated roving specimens showed good adhesion between sleeve filaments and matrix but significant differential displacement between core and sleeve filaments, whereas coated rovings exhibited more uniform behaviour with no detectable slip between filaments at the unloaded end.

High drapability associated with textiles offers significant design potential for innovative concrete structures. However, current textiles are often impregnated with rigid polymeric resins, which limit their flexibility. Scheurer et al. [126]examined the behaviour of pre-impregnated textiles cured within concrete, enabling the creation of intricate, curved components with strong mechanical properties essential for advanced manufacturing. Carbon rovings were impregnated with various materials, cured within the concrete, and then compared to rovings cured outside of the concrete. A rolling ball test revealed that all materials must be inserted into concrete within 4 to 24 hours after impregnation. Uniaxial tests on reinforced concrete showed significant strength improvement with impregnated textiles: epoxy resin (+185%), styrene butadiene rubber (+95%), water-dispersed epoxy (+165%), and polycarbonate polyurethane dispersion (+135%). Although concrete-cured textiles performed slightly lower than pre-cured ones, they still outperformed non-impregnated controls: epoxy resin (+34%) and styrene butadiene rubber (+38%). Water-dispersed epoxy resin demonstrated the highest potential for additive manufacturing methods like 3D printing and extrusion due to its robust performance and strong bonding properties.

2.10.2 Mineral-impregnated carbon fibre composites

Mineral-impregnated carbon fibre composites (MCF), developed at TU Dresden's Institute of Construction Materials, are an innovative reinforcement material [127]. The impregnation suspension consists of micro-cements, silica fume, water, and chemical admixtures. MCF offers the advantages of existing carbon fibre reinforcements while addressing the limitations of polymer-impregnated types. It performs well at high temperatures, provides better bonding with concrete, and allows for greater technological flexibility in automated production. Additionally, MCF is expected to be more cost-effective and sustainable than polymer-based reinforcements [128].

Continuous production of MCF is challenging due to the specific properties of carbon fibres. Their small diameters and high counts require full impregnation, yet the fine filaments can hinder mineral penetration. Achieving high fibre volume fractions and packing densities is difficult because of the size discrepancy between mineral particles and carbon filaments. To overcome this, particle sizes must be reduced through high-energy milling or the use of intrinsically micro-sized particles. Mechanical force via deflection ensures proper impregnation, and thermodynamic challenges from slurry chemical reactions must be managed. Improving the wettability and adhesion of carbon fibres can be achieved through treatments like plasma, anodic oxidation, or silica and calcite coatings. Post-impregnation treatments, such as hydration acceleration or form-fitting stitching, enhance functional robustness [129].

A fully automated device was employed for continuous carbon yarn impregnation with a mineral-based suspension [130]. This device, featuring a five-roller foulard for yarn deflection, guidance, and final shaping, ensured excellent penetration and efficient production at a speed of 360 m/h. The yarn was immersed in the suspension, deflected five times, and then shaped using a nozzle before being assembled on a hexagonal wheel for further processing, highlighting the industrial production potential of MCF (Figure 2.24).

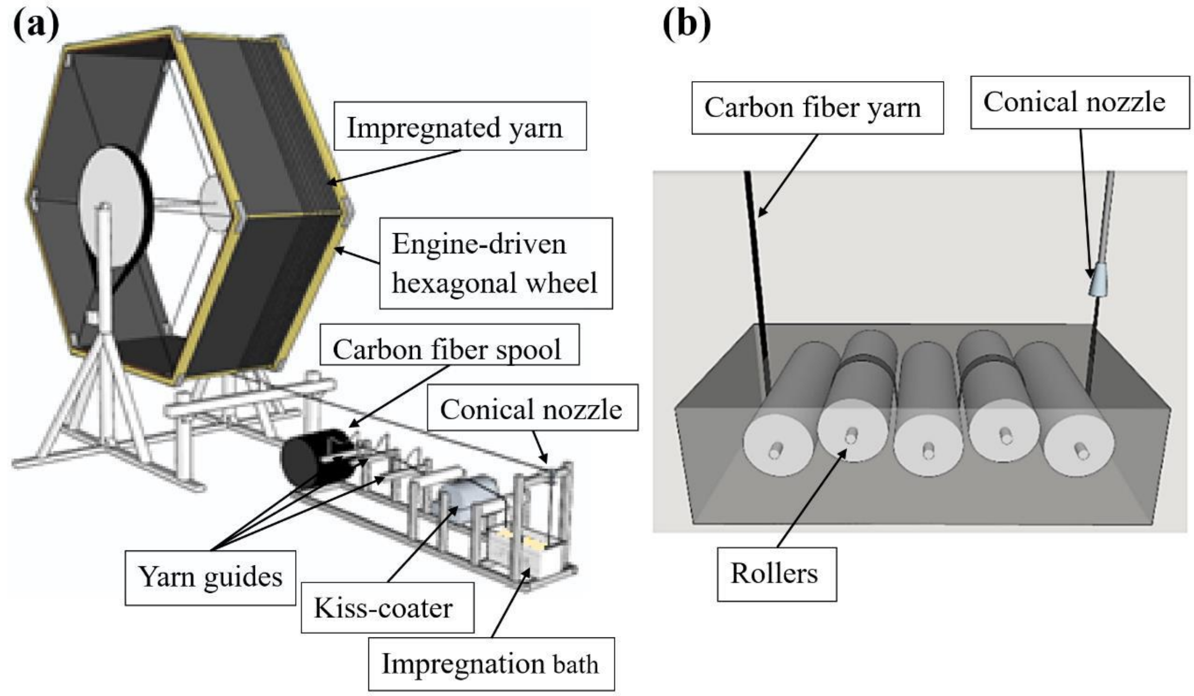


Figure 2.24 Diagram of the yarn impregnation device: (a) full setup, (b) processing in a five-roller foulard, and final shaping[130].

2.10.3 Plasma treatment

Plasma treatment was used to enhance the interaction of carbon multifilament roving with a mineral-based coating, improving load transfer to the concrete matrix [131]. Different plasma processes resulted in varying interfacial bonding characteristics. Oxygen plasma-treated carbon fibre showed the most significant mechanical improvement, ensuring consistent load transfer between carbon yarns. However, longer treatment times led to decreased performance due to carbon fibre oxidation. Plasma-driven functionalization shows promise for enhancing the fibre-matrix bond in carbon concrete composites without petrochemical impregnation.

2.10.4 Nano coating

Nano-coatings applied to alkali-resistant glass fibres have significantly enhanced durability through self-crosslinking styrene–butadiene polymer [132]. These coatings improve tensile strength, adhesion, and fracture energy absorption in cement composites. Coated filaments-maintained contact stiffness even after alkaline treatment, exhibiting excellent alkaline resistance [133].

Koeckritz et al. [134] demonstrated that self-cross-linking styrene-butadiene (SB) copolymer-coated fabrics exhibited superior mechanical properties in textile-reinforced concrete (TRC). Weichold and Möller [135] found that PVA reactive coatings dispersed in non-hydrated cement improved fibre-matrix interaction, resulting in significantly higher pull-out load (three times) and pull-out work (fifty times) compared to commercial AR glass multifilaments. Polymer dispersion enhanced interaction, providing higher frictional resistance during pull-out with slip-hardening behaviour.

Tyagi et al. [136]used computer simulations to study the impact of nanocomposite polymeric fillers on coating damaged surfaces, finding them effective in reducing stress concentration at defect zones. They noted the importance of chemical compatibility between substrate and filler for proper bonding and enhanced mechanical behaviour.

A subsequent study by Weichold[137]reported a remarkable 400% enhancement in pull-out strength using a reactive coating of soluble polymer and non-hydrated cement. Uncoated multifilament bundles were found to have inferior durability, whereas coated bundles in fabric behaved similarly to monofilament structures, significantly influencing water transport within the concrete matrix [138]. Additionally, cracked TRC specimens exhibited reduced fluid ingress into the innermost concrete area [139].

2.10.5 Resin coating of woven fabric

A lightweight TRC was created by embedding carbon woven leno fabric (warp 24K, weft 12K, grid spacing 12 mm x 9 mm) in a cementitious matrix with ordinary Portland cement, silica fume, expanded glass fine aggregate, superplasticizer, and water (Pham et al. 2022). Figure 208 shows carbon fabric coated with epoxy, sand, and aluminium powder. These coating techniques significantly impacted the failure modes, crack features, tensile strengths, and deformation capacities of the lightweight TRC composites. Figure 2.25demonstrates how different coatings affected tensile properties such as crack stress, ultimate stress, strain at ultimate stress, crack stiffness, and tensile toughness.

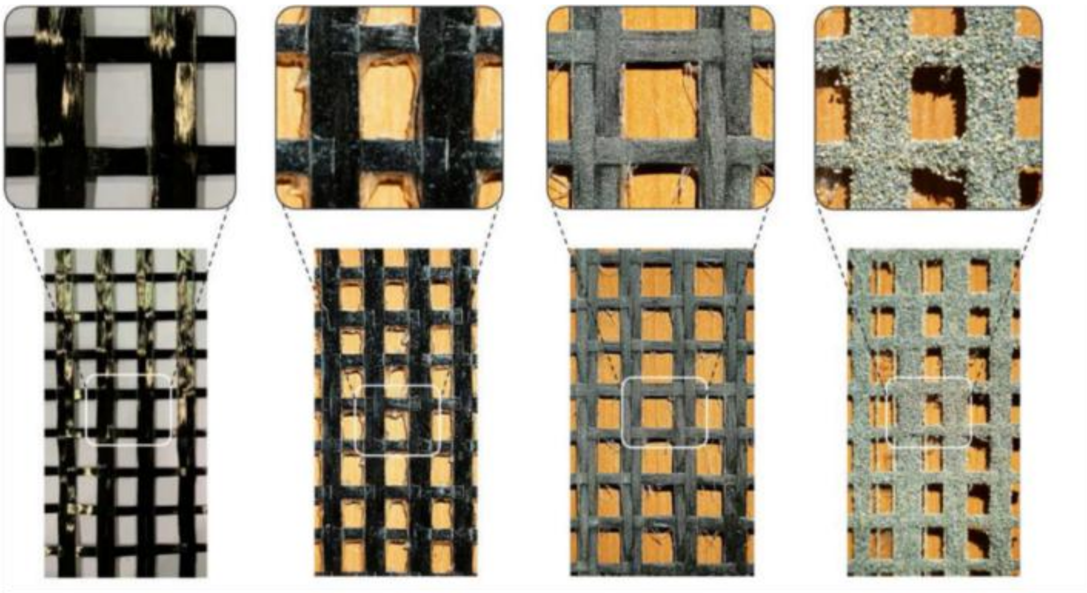
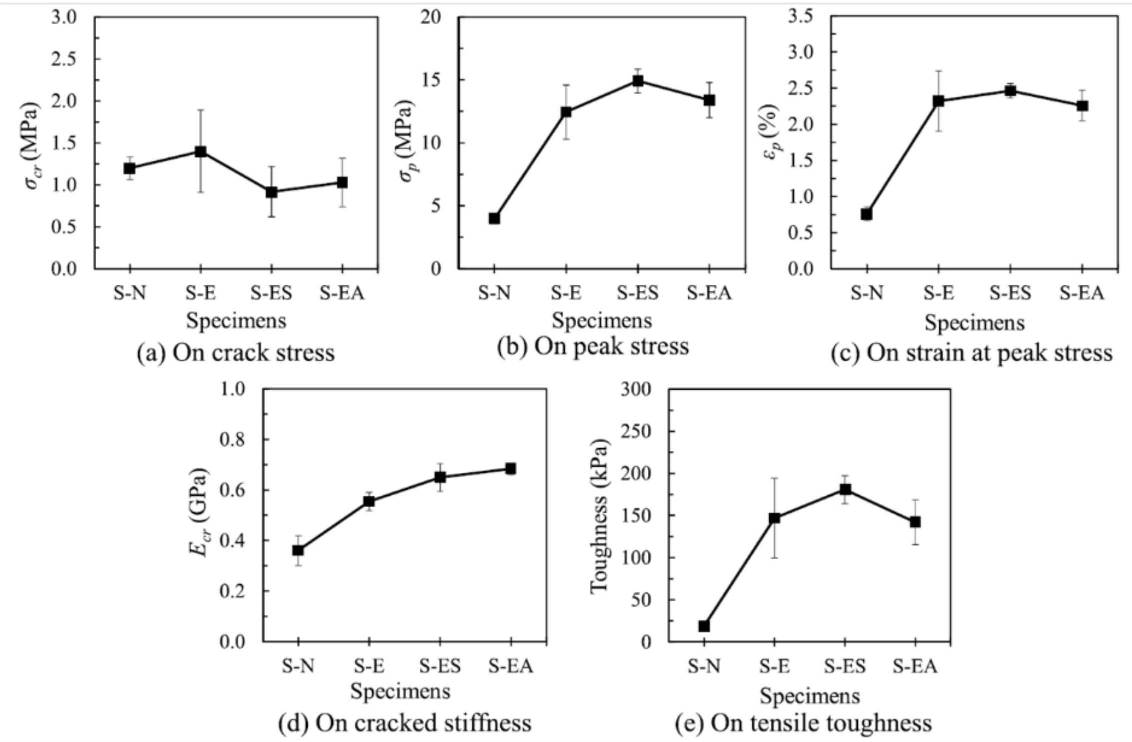


Figure 2.25 Images illustrating various surface coatings applied to carbon[140].

Initially, all coated carbon TRCs showed similar first crack stress (Figure 2.26, a). However, after the first crack, coated carbon fabrics in TRC specimens exhibited significant improvements in peak stress, peak strain, crack stiffness, and tensile toughness compared to uncoated fabric specimens (Figure 2.26, b-e). Epoxy-impregnated (S-E), epoxy with sand coating (S-ES), and epoxy with aluminium oxide coating (S-EA) improved peak stress by 213%, 275%, and 237%, respectively, compared to uncoated specimens. TRC specimens with epoxy-coated carbon fabric displayed splitting cracks along the length during uniaxial tensile testing due to poor bonding between the epoxy coating and the cementitious matrix. Adding rough coatings like sand and aluminium powder enhanced crack features (more cracks and narrower widths) and increased crack stiffness by reducing splitting crack width. This improvement resulted from the enhanced bond quality at the fabric-matrix interface due to the surface roughness provided by the sand and aluminium oxide coatings, which strengthened adhesion within the mortar matrix and minimized splitting cracks from weak polymer-to-mortar bonding.



Specimen details:
S-N – Uncoated (dry) fabric, S-E – Epoxy impregnated fabric, S-ES – Epoxy impregnated fabric with sand coating, S-EA – Epoxy impregnated fabric with Al_2O_3 coating

Figure 2.26 Influence of different surface coatings on the tensile properties of carbon TRC specimens[140].

In another study, plain-woven flax fabric underwent thread removal to create three fabrics with areal densities of 135 g/m², 180 g/m², and 210 g/m², featuring open areas of 0.775, 0.733, and 0.693 respectively. These flax fabrics were then impregnated with an epoxy resin and hardener mixture at varying ratios (0.6, 0.8, and 1.0). The study investigated the compression and impact properties of concrete specimens reinforced with resin-impregnated fabric [141]. Compared to plain concrete, specimens reinforced with flax fabric showed a 2-4-fold increase in compressive strength, a 5-10-fold increase in impact resistance, and a 1.1-2.3-fold increase in impact crack propagation. Figure 2.27 illustrates that concrete specimens reinforced with fabric impregnated using a lower hardener-to-epoxy resin ratio of 0.6 exhibited a favourable impact response.

Figure 2.27 Damage comparison of unreinforced and flax fabric reinforced concrete specimens after repeated hammer impact blow[141].

2.11 Inclusion of short fibres as secondary reinforcement in TRC

The incorporation of discrete fibres (secondary reinforcement) alongside fabric (primary reinforcement) has enhanced the mechanical properties of TRC. Research examined the impact of adding short carbon and AR glass fibres (0.5% and 1.0% volume fraction, 6 mm length) on the fracture behaviour of AR glass biaxial reinforced concrete [142]. Carbon and AR glass fibres increased the first crack stress by 1.5 and 2 times respectively, with a moderate increase in tensile strength. The water-to-binder ratio (w/b) influenced fibre-matrix bonding and failure patterns: lower w/b (0.3) favoured fibre fracture, while higher w/b (0.45) showed fibre pull-out. The bond between filaments and the cementitious matrix varied along the yarn's length, forming adhesive cross-links between matrix and filament (Figure 2.28, a). Microscopic analysis revealed that randomly dispersed short fibres in the matrix created new cross-links with the matrix, improving yarn-matrix interaction, reducing matrix relaxation near cracks, and forming finer cracks (Figure 2.28, b). Stress–strain curves (Figure 2.29) of TRC specimens with moderate textile reinforcement (2 layers), with and without 1.0% volume of short AR glass fibres (SGF) and carbon fibres (SCF), demonstrated that short fibre addition increased initial crack stress but did not improve tensile strain capacity; in fact, it slightly decreased it.

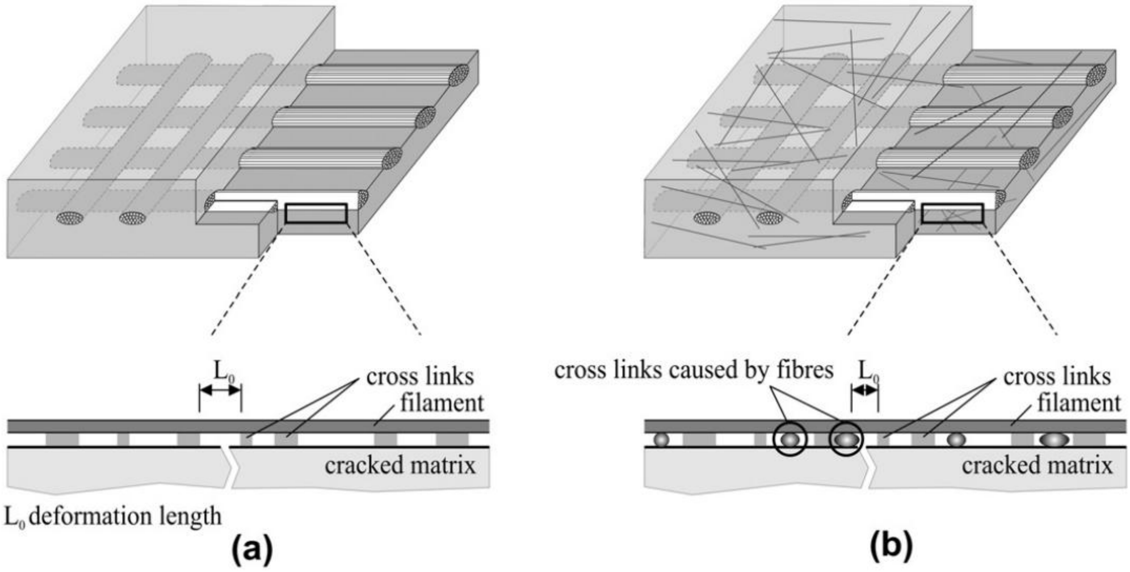


Figure 2.28 Cross-linking mechanism in TRC specimens: (a) without the presence of short fibres, and (b) with the incorporation of short fibres[142].

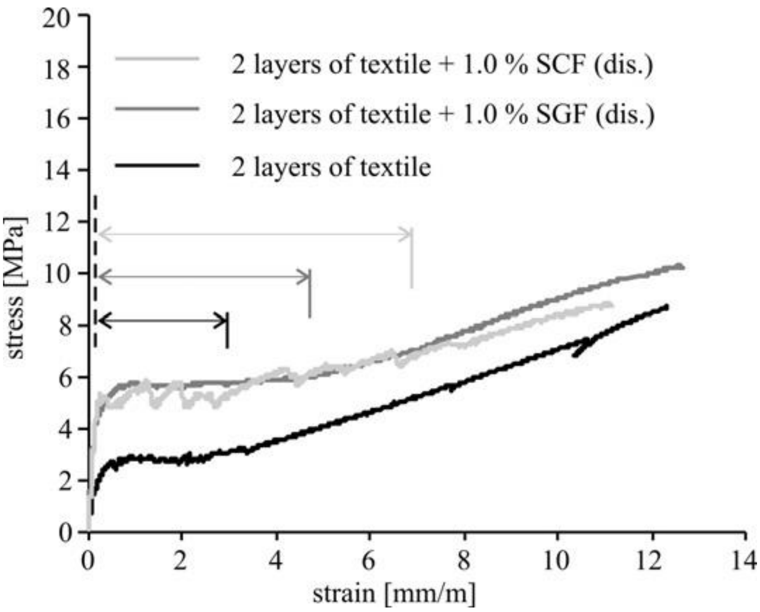
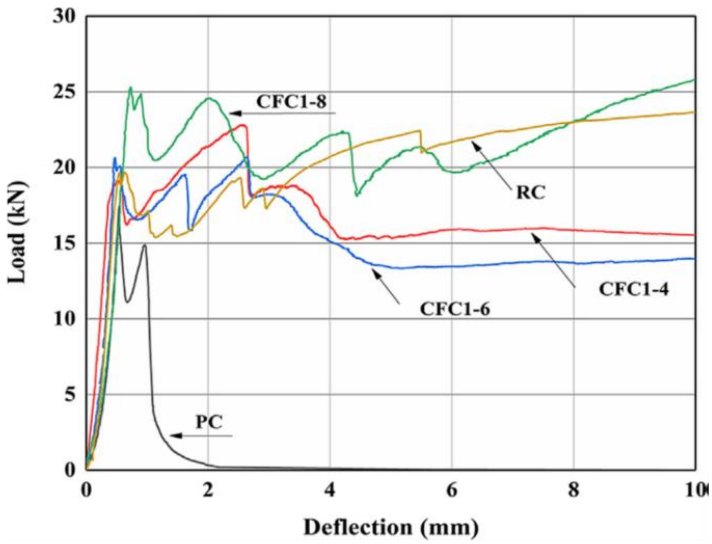


Figure 2.29 Influence of SGF and SCF incorporation on the multiple cracking behaviour in TRC plates subjected to tensile loading[142].

In another study, researchers investigated the flexural load-bearing and energy absorption capacity of concrete slabs reinforced with hybrid materials: basalt fabric (mesh size 5 mm x 5 mm) and short polypropylene fibres (aspect ratio 56, length 45 mm) [143]. Compared to plain concrete slabs (PC), the basalt TRC slab showed a 27% increase in load-bearing capacity and a 697% increase in toughness. Combining polypropylene fibres with basalt fabric synergistically enhanced the load-bearing capacity, toughness, multiple cracking behaviour, and ductile failure of TRC specimens. When compared to a steel-reinforced concrete (RC) slab (with 0.31% steel content), the hybrid TRC with a single layer of basalt textile and 8 kg/m³ of polypropylene fibres (CFC1-8) exhibited a 7% increase in load-bearing capacity and a 4.5% increase in toughness (Figure 2.30). The authors suggested that this hybrid basalt TRC with added polypropylene fibres could potentially replace steel mesh-reinforced concrete (RC) slabs.



Note: TRC slab specimens
CFC1-4 – 1 layer of basalt fabric + polypropylene fibre content of 4 kg/m³
CFC1-6 – 1 layer of basalt fabric + polypropylene fibre content of 6 kg/m³
CFC1-8 – 1 layer of basalt fabric + polypropylene fibre content of 8 kg/m³

Figure 2.30 Flexural load-deflection properties of plain concrete slab (PC), steel-reinforced concrete slab (RC), and hybrid TRC slab with polypropylene and basalt (CFC1-4, CFC1-6, and CFC1-8)[143].

The surface of unidirectional carbon fibres was epoxy-coated prior to fabricating TRC specimens, which included polyvinyl-alcohol (PVA) fibres (0.5% V_f, 6 mm length). This resulted in a significant 43% improvement in bond strength and a 56% increase in load-bearing capacity of the carbon fabric TRC. However, excessive fibre dosage can diminish TRC properties, necessitating controlled application for optimal mechanical performance in repair and strengthening applications [144]. Subsequent research investigated PVA staple fibres (V_f 0.5, 1, and 2%, 12 mm length) in carbon woven TRC, showing that higher PVA content led to increased multiple cracking with reduced crack spacing. The transition from slippage to fracture in failure mode was attributed to fibre integration and crosslinking effects. Addition of 2% PVA fibres enhanced tensile stress by 106%, 128%, and 87% for reinforcement ratios of 0.35%, 0.70%, and 1.05% in a cementitious matrix with higher fly ash content [145].

Incorporating dispersed short PVA fibres into dry carbon TRC composites significantly enhances both pre-cracking and post-cracking tensile performance [140]. PVA1.2-N (1.2% fibre volume) shows a 163% improvement in peak stress compared to the reference (PVA0-N), with a strain capacity up to 1.6%. PVA fibres bridge stress across fine cracks and establish additional cross-links during hydration, improving fabric-matrix bonding. However, the benefits were less pronounced in pre-cracking of epoxy-coated lightweight TRC composites. Nevertheless, adding 0.8-1.2% short PVA fibres substantially enhances crack characteristics by reducing width and delaying splitting cracks at the fabric-matrix interface, thereby increasing overall tensile strain and toughness in cracked TRC specimens.

2.12 Mechanical characteristics of FRCM specimens

2.12.1 Strain-softening and strain-hardening response of FRC composites

The stress-strain (or stress-elongation) curve of a strain-softening FRC composite (Figure 2.31, a) typically begins with a steep initial ascent up to the first percolation crack (part I), which corresponds to the maximum stress point. Here, the crack becomes critical, marking the onset of crack localization. Subsequently, the resistance drops, no new cracks develop, and only the critical crack widens with increased deformation. The descending branch of the curve (part III) mainly represents the load versus the opening of the critical crack, with stress always lower than the peak stress at first cracking. In this phase, fibres may pull out, fail, or exhibit a combination of these behaviours, and the cement matrix's contribution is generally negligible [40].

In a strain-softening composite after first cracking (part III), the maximum post-cracking stress (σ_{pc}) is lower than the stress at first cracking (σ_{cc}). The elongation corresponding to σ_{pc} can be similar to or substantially larger than that at σ_{cc}, depending on fibre reinforcing parameters such as bond strength, elastic modulus, and fibre content. Since only one crack develops, the composite's elongation is mainly due to the crack opening, which cannot be translated into strain for the entire specimen but only describes the crack width [40].

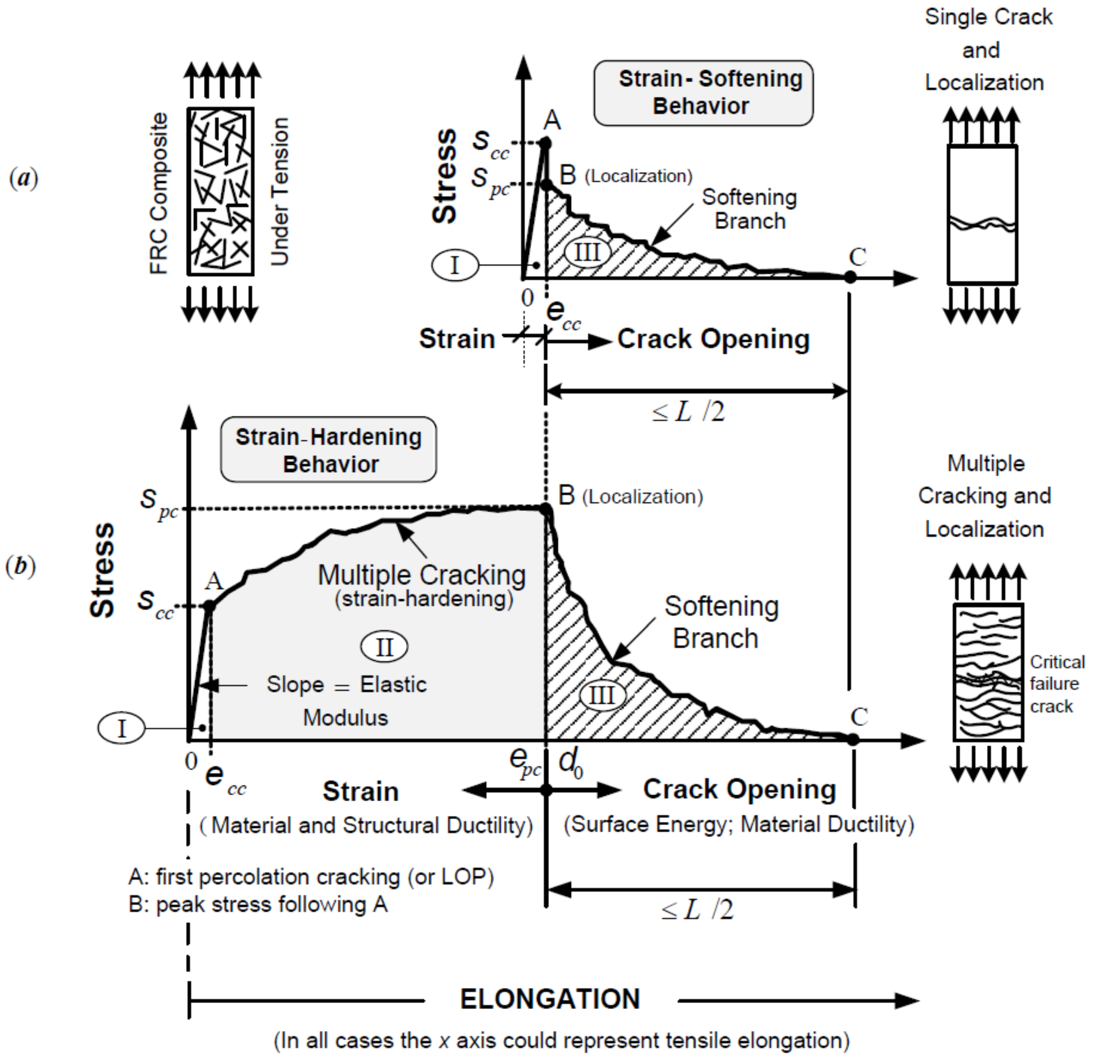


Figure 2.31 Typical stress-strain or stress-elongation curves under tension until complete separation: (a) Conventional strain-softening FRC composite, (b) Strain-hardening FRC composite (often referred to as HPFRC composite)[40].

The stress-strain curve of a strain-hardening FRC composite (Figure 2.31, b) initially follows the same path as a strain-softening composite (part I). However, it is followed by a strain-hardening phase where multiple cracks develop and significant energy is absorbed (part II). In this phase, fibres bridge the first crack and resist the tensile load, allowing multiple cracks to form in the matrix at stresses equal to or higher than the cracking strength. This continues until the cracks stabilize at a certain spacing and width. With further elongation, one crack becomes critical at maximum post-cracking strength (σ_{pc}, ϵ_{pc}), leading to fibre pull-out or failure, and a decrease in resistance (part III). After σ_{pc}, the resistance drops, the critical crack widens, and the widths of other cracks decrease. The descending branch is similar to that of a strain-softening composite [40].

Before crack localization, the composite's elongation can be translated into tensile strain. After localization, it translates into crack opening or member elongation. The critical failure crack may appear as a smeared crack with branches and micro-cracks. This suggests strain-hardening composites have $\sigma_{pc} \geq \sigma_{cc}$, while strain-softening composites have $\sigma_{pc} < \sigma_{cc}$ (Figure 2.31) [40].

2.12.2 Yarn pull-out behaviour in FRCMspecimens

The pull-out behaviour of straight and crimped yarns within a FRCM follows a similar pattern, as shown in Figure 2.32. The graph is divided into three zones:

Zone A - Elastic Zone: Here, the deformation of the fibre and matrix is equal until the critical load (P_{cr}) is reached, where the shear stress matches the elastic bond strength (τ_{au}).

Zone B - Debonding Zone: In this zone, the pull-out load (P) exceeds the critical load (P_{cr}), causing the shear stress to surpass the elastic bond strength (τ_{au}). As the pull-out load increases, debonding progresses, and the interfacial shear stresses become constant and frictional.

Zone C - Friction Zone: When debonding extends beyond the embedded length (l_e), complete debonding occurs, and the filament experiences dynamic pull-out with frictional shear stress.

The yarn pull-out resistance consists of two components: elastic (adhesion shear stress, τ_{au}) and slip (friction shear stress, τ_{fu}), with frictional stress contributing more to the pull-out resistance than adhesion stress [146].

The average bond stress in a pull-out test can be calculated using the equation[125]:

$$Average\ Bond\ stress\ (\tau_b) = \frac{Pull\ out\ force\ (F_r)}{Nominal\ contact\ surface\ (U_r \times l_e)} \ldots Eq. (1)$$

Where, U_r is the contact perimeter of the roving (yarn) measured using microscope, and l_e is the embedment length of the roving (yarn) inside cementitious matrix.

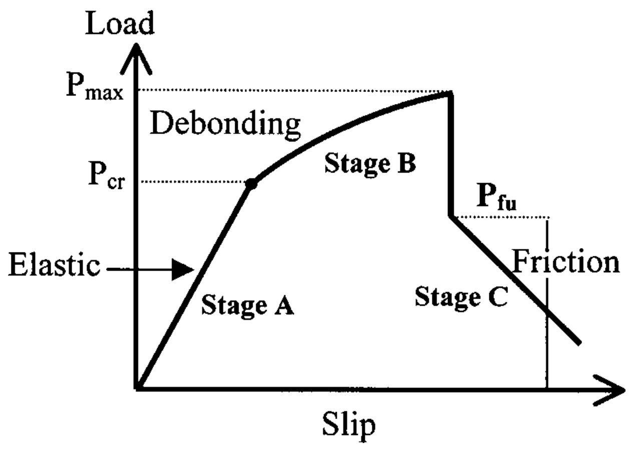


Figure 2.32 Illustration depicting a standard load-deformation curve derived from yarn pull-out testing of FRCM[146].

2.12.3 Uniaxial tensile behaviour of FRCM specimens

The stress-strain behaviour of FRCM under uniaxial tension, as depicted in Figure 2.33, exhibits three distinct zones. Zone I shows nearly linear-elastic behaviour, governed by the stiffness of the matrix and fibres. Zone IIa displays quasi-ductile behaviour with multiple fine cracks due to increased stress, influenced by fabric-matrix bond integrity and fibre volume. In Zone IIb, cracks widen until reaching ultimate stress, where load is primarily borne by multifilament yarns, leading to eventual failure of the FRCM.

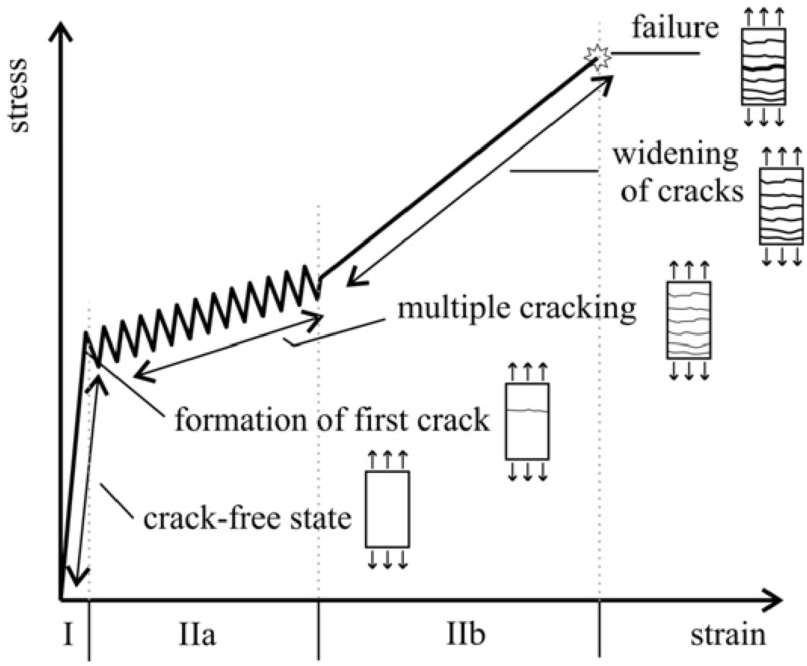


Figure 2.33 Tensile stress-strain characteristics of FRCM under uniaxial loading[142].

2.12.4 Flexural behaviour of FRCM specimens

The flexural behaviour of FRCC is depicted in Figure 2.34, showing distinct zones. Zone (a) displays linearly elastic behaviour where stresses are distributed between concrete and fabrics without composite fracture. As concrete cracks in zone (b), load decreases as the crack widens, transferring load to the fabrics. Fabrics progressively bear the load in zone (c), relying on yarn strength and fabric-matrix bonding. Well-reinforced specimens in zone (c) exhibit strain-hardening, exceeding the first crack load to achieve higher ultimate loads. Conversely, under-reinforced specimens experience strain softening, failing to surpass the first crack load. Higher reinforcement ratios and additional fabric layers enhance the likelihood of strain-hardening behaviour, resulting in higher ultimate loads. Ultimately, fabric failure initiates within the yarns in zone (d), leading to load reduction until fabric failure occurs [99].

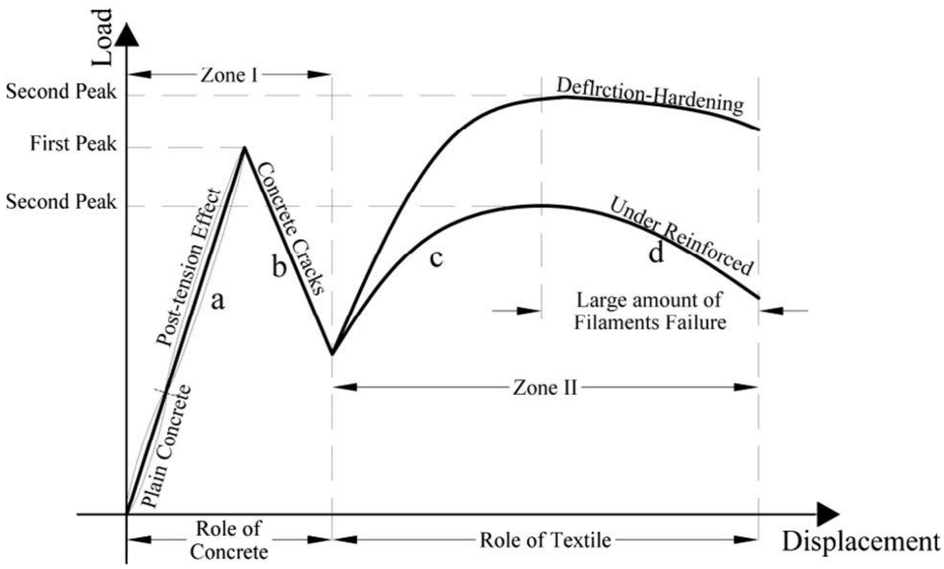


Figure 2.34 Load-deflection characteristics of FRCMunder flexural loading[99].

2.13 Gaps in Literature

1. Hybrid structures (yarn and fabric) have been shown to improve the mechanical properties of FRCM [28]–[32], [34], [35], but there are limited studies on hybrid yarn-based structures for FRCM reinforcement.
2. The use of core-sheath hybrid yarns with a low modulus sheath fibres and high-performance core filaments in FRCM has not been explored in the literature.
3. Research on improving the fibre-mortar bond in FRCM through mechanical anchorage is limited. While some studies exist for braided structures, no studies have been reported for woven fabric reinforced concrete, excluding methods such as woven fabric weave parameters, sand and resin coating.
4. Numerous studies have compared the mechanical properties of FRCM reinforced with carbon, basalt, AR glass, and aramid. However, due to differences in grid opening or yarn tex, proper comparisons are challenging to establish.
5. Many studies have compared the mechanical characteristics of TRC reinforced with fabrics made from carbon, basalt, AR glass, and aramid. However, since these fabrics were procured from different suppliers, variations in resin and coating make it difficult to establish proper comparisons.
6. No studies have directly compared the mechanical characteristics of uncoated, thermoset, and thermoplastic fabric composite reinforcement in FRCM.

This study aims to address these gaps in the literature.