

CHAPTER – 3

MATERIALS AND METHODS

This chapter begins with the selection of fibres and the basic characteristics of raw materials (fibre, resin, and mortar ingredients). It continues with hybrid yarn development, thermal treatment, fabric formation, compression moulding, epoxy coating, yarn sample preparation for microscopic cross-section examination, fabrication of formwork for mortar specimen fabrication, mortar formulation and mix design, slump test for examining mortar workability, mortar mixing, casting, curing, and different specimen preparations. This is followed by the mechanical characterization of yarn, fabric, and mortar specimens: tensile tests of yarn, fabric, and composites, yarn pull-out test, uniaxial tensile test, and flexural test by three-point bending of fabric-reinforced cementitious mortar (FRCM) specimens.

3.1 Raw material selection

3.1.1 Types of filament rovings and fibres used

Basalt, carbon, and AR glass are the most common high-performance filaments preferred for concrete reinforcement due to their excellent mechanical and durability properties are used for the development of fabric reinforcement for mortar specimens. For hybrid yarn development, low-modulus ductile fibres such as polypropylene (PP) staple fibres in sliver form and twisted polyester multifilament yarn are used. The different fibres or filaments used in this study are shown in Figure 3.1 and the important characteristics are listed in Table 3.1.



Figure 3.1 Different raw materials (fibre, yarn and sliver) used for producing core-sheath hybrid yarn.

Table 3.1 Basic characteristics of the yarns (rovings/tow) used in this study.

Specification	Basalt Roving	Alkali Resistant (AR) Glass Roving	Carbon Roving	Polyester yarn	Polypropylene Sliver
Manufacturer	KamennyVek, Russia	Owens Corning	Toray, Japan	FairdealPvt. Ltd., Surat, India	Zenith fibres, Vadodara, India
Fibre/Filament type	Multifilament (untwisted)	Multifilament (untwisted)	Multifilament (untwisted), 6K	Multifilament(twisted)	Staple fibre(length – 50 mm)
Linear density of single strand (tex)	1200	2500	360	160	5700(fibre denier 2.5)
Linear density of filament bundle used in this work (tex)	1200 x 2 bundle = 2400	2460 x 1 bundle = 2460	360x 7 bundle = 2520	<ul style="list-style-type: none"> • Twisted (11 filaments) • Braided (8 filaments) 	-
Filament diameter (μm)	13	14(No. of strands: 30, Strand tex: 82)	7	-	-
Specific gravity (g/cm^3)	2.67	2.68	1.76	1.38	0.9
Tensile strength (MPa)	2700	1000	4900	-	-
Modulus of Elasticity (GPa)	85	72	230	-	-

3.1.2 Epoxy resin and hardener

The epoxy resin and hardener were procured from Purnima Enterprise, located in Kalol, Gujarat. The properties of the resin and hardener are listed in Table 3.2.

Table 3.2 Basic properties of the resin and hardener.

Parameters	Epoxy resin	Hardener
Product Name	PE 606 Epoxy resin	Epoxy hardener and DMP 30
Viscosity (mPa.s)	12990	182.3
Epoxy value (eq. gram)	5.37	-
Amine value (mg KOH/gram)	-	612.5
Density (g/cm ³)	1.16	0.98

3.1.3 Components of Mortar mix

Among the mortar constituents, cement of grade OPC 53 is procured from Ultratech, supplied by their supplier in Bhavnagar, Gujarat. The fly ash and ultrafine GGBS are sourced from Suyog Elements India Private Limited, located in Palej, Bharuch, Gujarat. Silica fume is obtained from Guru Metachem, based in Ahmedabad, Gujarat. The polycarboxylate ether (PCE) based superplasticizer Auramix 400 is procured from Fosroc Chemicals (India) Private Limited in Ahmedabad, Gujarat. The polypropylene chopped fibres, with 60 mm length and 6 denier fineness were utilized in the mortar and were procured from Zenith Fibres in Vadodara, Gujarat. The different mortar ingredients used for mix design is shown in Figure 3.2 and the basic properties of the different binders are listed in Table 3.3.

Table 3.3 Properties of the different binders as mortar constituents.

Parameters	Cement	Fly ash	Ultrafine GGBS	Silica fume
Manufacturer/Supplier	Ultratech OPC 53	Suyog Elements India Pvt. Ltd.	Suyog microfine -Ultrafine GGBS	Guru Metachem
Specific gravity (g/cm ³)	1.44	2.2	2.88	2.22
Fineness (m ² /kg)	328	417.68	3038	18800

Particle size (μm)	2.3	10-180	0.59 – 14.5	0.1-0.2
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Constituents of Mortar used for fabricating TRC specimens:
a – cement; b – silica fume; c – GGBS; d – river sand; e – crushed stone; f – fly ash;
g – PCE based superplasticizer; h – polypropylene staple fibres; i – water.

Figure 3.2 Different constituents used for mortar preparation.

3.2 Development of Hybrid yarn structures

3.2.1 Core-sheath yarn development using the DREF 3 spinning system

In this study, a DREF3 friction spinning system was used to produce core-sheath yarn structures as shown in Figure 3.3. Core strand of the yarn consist of untwisted bundle of basalt, carbon and AR glass whereas, polypropylene (PP) staple fibres are used as sheath. PP slivers are fed from the back side of machine which are drafted and individualized using a rotating saw-tooth carding roller. Individualized fibres come into contact with a continuous filament strand (basalt, carbon and AR glass) on a rotating perforated friction drum, creating the yarn through frictional contact. The resulting DREF yarn structure features a sheath of PP staple fibres uniformly covering the central filament strand (basalt, carbon and AR glass). Sheath fibres exert a transverse force, enhancing inter-filament binding and preventing

slippage and abrasion during subsequent processing. The process parameters in DREF3 spinning machine are listed in Table 3.4.

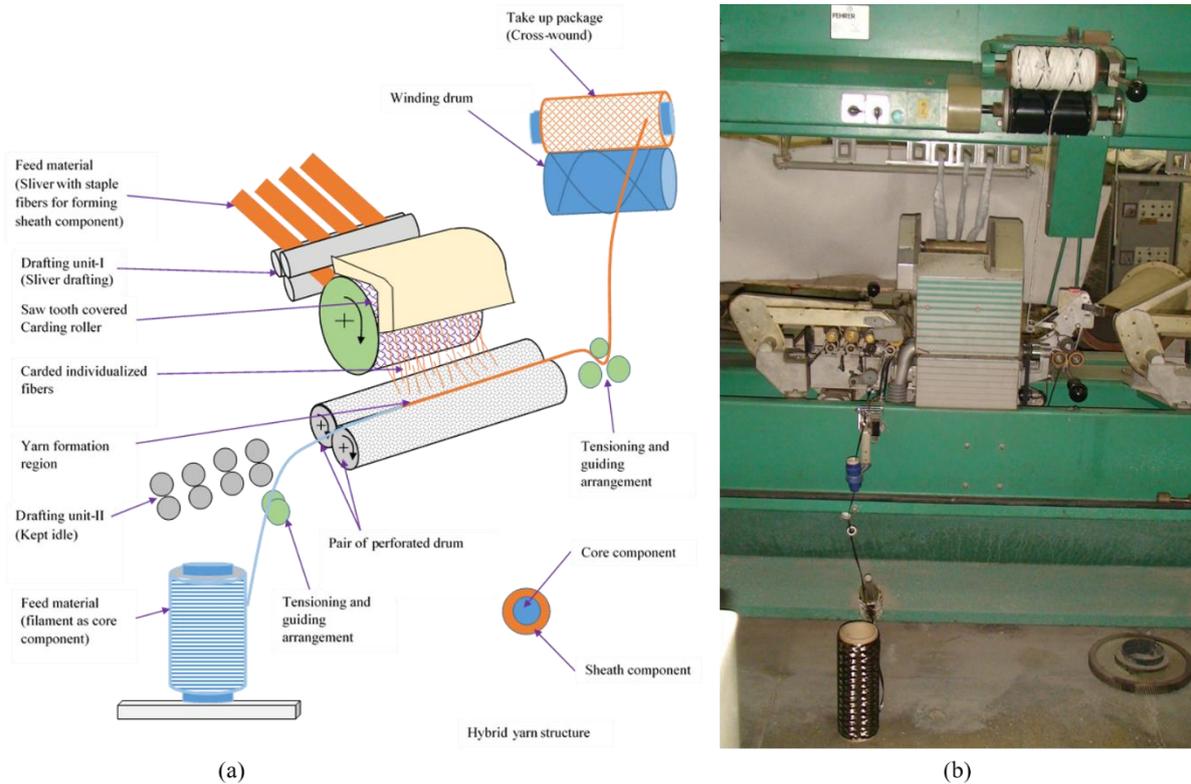


Figure 3.3 DREF3 spinning machine (a) schematic representation[22], (b) actual machine (FEHRER, Model DREF 3000, used for sample preparation(Available in the Department of Textile and Fibre Engineering, IIT Delhi).

Table 3.4 Process parameters in DREF3 spinning machine.

DREF3 spinning parameters	Values
Linear density of PP sliver fed	5700 tex
Number of PP sliver fed	3
Rotational speed of spinning drum	3030 rpm
Drafting unit 1	1.90 m/min
Drafting unit 2	0.49 m/min
Winding speed	30 m/min
Core-sheath ratio in DREF yarn	75:25

3.2.2 Cable yarn structure development using the filament wrapping method

Cable yarns are produced by uniformly and spirally wrapping a surface filament strand (surface yarn) over a core filament strand without twisting the individual strands. The core filament provides load-bearing strength, while the surface filament protects the core from abrasion and offers a ribbed surface texture, which is intended to improve mechanical anchorage in TRC. A direct-twisting machine (Model-DirecTwist 2B, Ağteks Ltd., Beylikdüzü, Istanbul, Turkey) was used to produce the cable yarn, as shown in Figure 3.4.

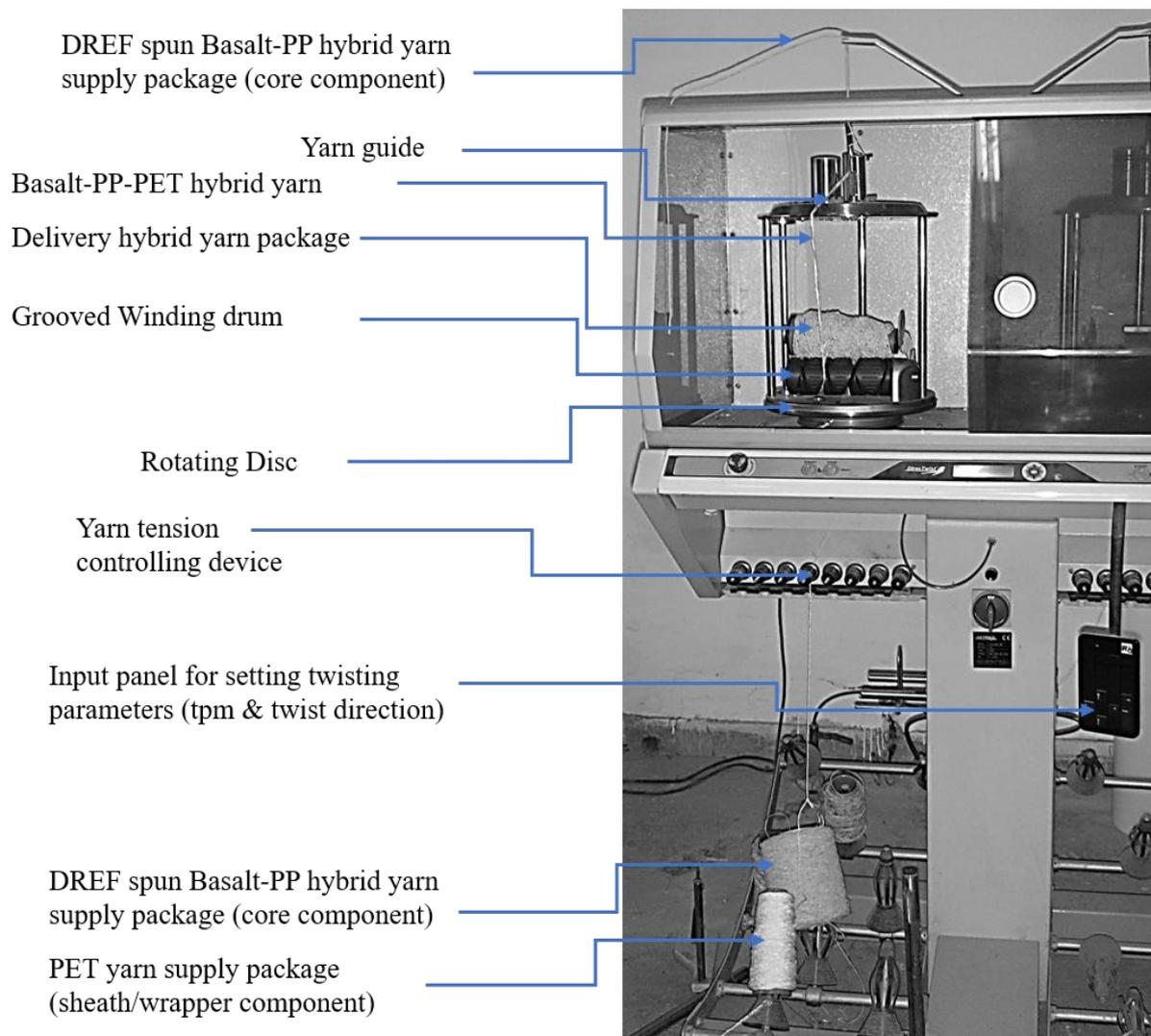


Figure 3.4 Direct twisting machine for filament wrapping (Model-DirecTwist 2B, Ağteks Ltd., Beylikdüzü, Istanbul, Turkey, used for sample preparation (Available in the Department of Textile and Fibre Engineering, IIT Delhi).

Three different types of yarn structures were formed using this machine. In the first structure, ten PET parallel-laid filament yarns were wrapped around a single PET filament

yarn(core strand),creating a wavy surface texture (Figure 3.5a). In the second structure, a core strand of high-performance filaments was helically wrapped with a fine polyester yarn (Figure 3.5b). In the third structure, a DREF-spun core-sheath yarn structure consisted of a high-performance filament strand in the core, covered with a sheath of staple PP fibres and further helically wrapped with a fine polyester yarn (Figure 3.5c). The process parameter includes rate of twist insertion was 1300 twist/min (S-twist), and the helical wrapped yarn was formed with 200 twist/m. The machine parameters can be adjusted to select the wrap or twist density and twist direction (S or Z). However, the system has limitations when processing coarse, bulky yarns.

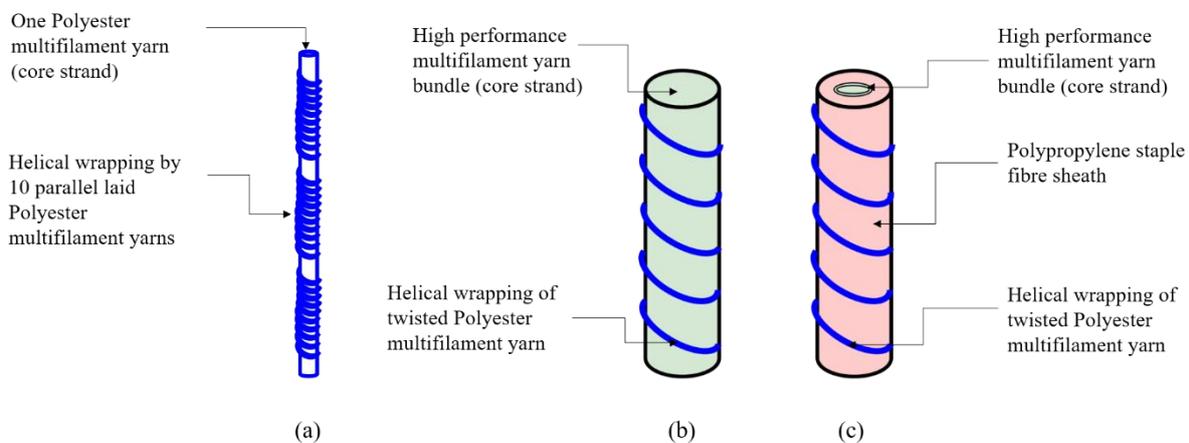


Figure 3.5 Schematic representation of different yarn structures formed on a direct twisting machine: (a) ten PET parallel-laid filament yarns wrapped around a single PET filament yarn (core strand); (b) a core strand of high-performance filaments helically wrapped with a fine polyester yarn; (c) a DREF-spun core-sheath yarn structure with a high-performance filament strand in the core, covered with a sheath of staple PP fibres and further helically wrapped with a fine polyester yarn.

3.2.3 Cable yarn structure development using the braiding method

Formation of coarse yarn is not possible using a direct-twisting machine. Therefore, to produce coarse yarn with a ribbed profile (helically wrapped yarn), a circular braiding machine is employed, as shown in Figure 3.6.

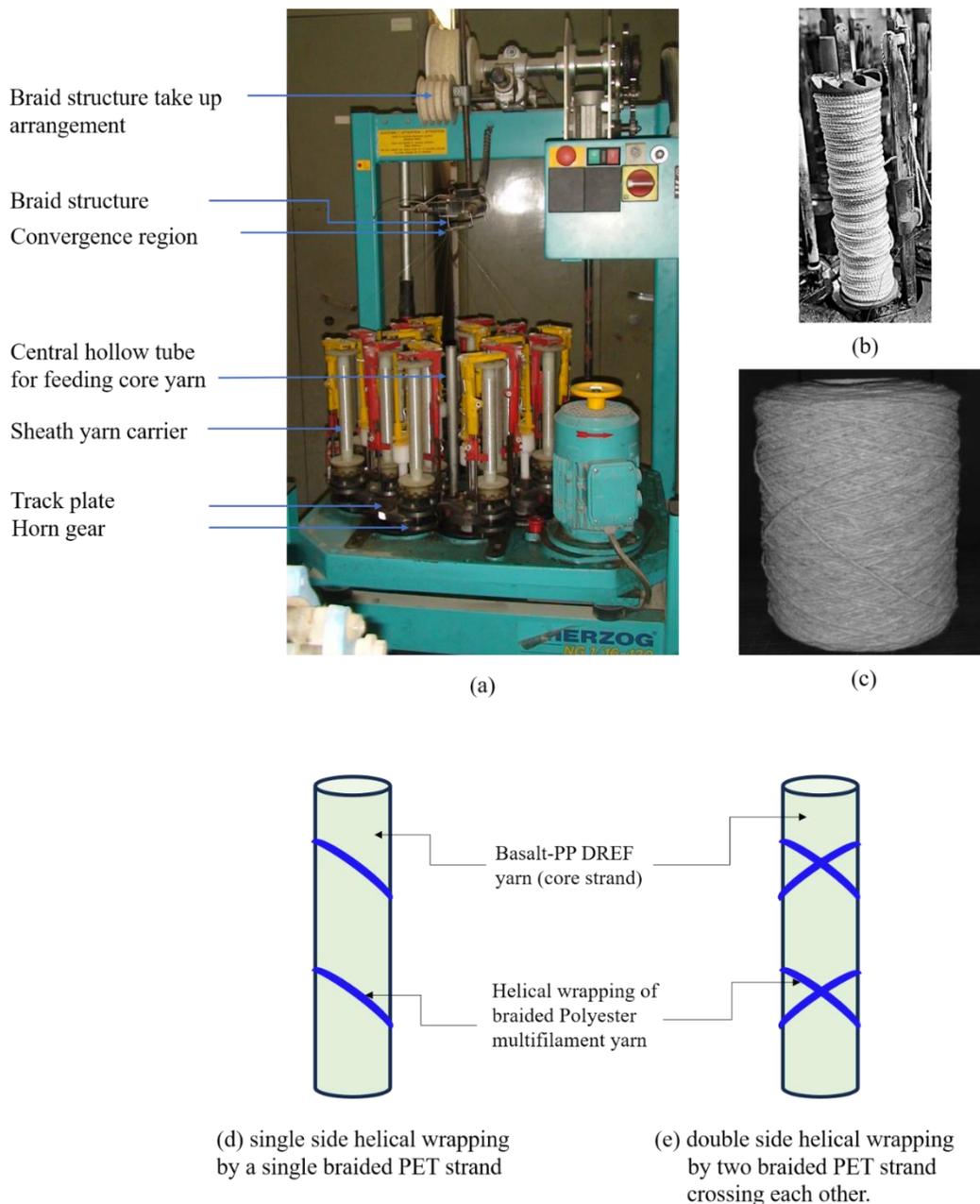


Figure 3.6 (a) Braiding machine, (b) out of 16 yarn carriers in the braiding machine, 15 carriers were idle and only one yarn carrier loaded with twisted multifilament polyester yarn was used for forming helical wrapping around the core yarn strand, (c) Basalt-PP (DREF yarn) as the core yarn package supplied from the central hollow tube, (d) schematic diagram of Basalt-PP (DREF yarn) as the core yarn package helically wrapped with an eight-yarn PET braided structure, (e) schematic diagram of Basalt-PP (DREF yarn) as the core yarn package helically wrapped on both sides using two strands of eight-yarn PET braided structure (Herzog, Model NG 1/16-120, used for sample preparation, available in the Department of Textile and Fibre Engineering, IIT Delhi).

Four different braided structures are developed using this machine:

(a) A braided PET yarn, formed by braiding eight single PET yarns (160 tex each) on an eight-yarn carrier braiding machine, with each carrier fed with a PET yarn.

(b) A hybrid yarn structure in which a Basalt-PP core-sheath DREF yarn serves as the core and is helically wrapped with an eight-yarn PET braided structure (comprising eight PET yarns) on one side, using one carrier in the braiding operation.

(c) A hybrid yarn structure similar to (b), but with the Basalt-PP core-sheath DREF yarn helically wrapped on both sides using two carriers in the braiding operation, with the braided PET yarns crossing each other.

(d) A hybrid yarn structure with a helically wrapped configuration, where a coarse yarn bundle of high-performance filaments is fed from the central portion of the circular maypole braiding machine through a hollow pipe. The machine consists of 16 yarn carriers, with a filled bobbin mounted on a single yarn carrier loaded with a 10/1 twisted PET yarn (Figure 3.5a). One complete rotation of the yarn carrier inserts a twist (wrap) into the central strand, resulting in the formation of a core covered with an outer helical wrap of yarn (cable yarn). The PET yarn is helically wrapped around the core strand at an angle of 21° relative to the vertical yarn axis.

3.2.4 Thermal treatment of twisted polyester yarn and hybrid yarn structures

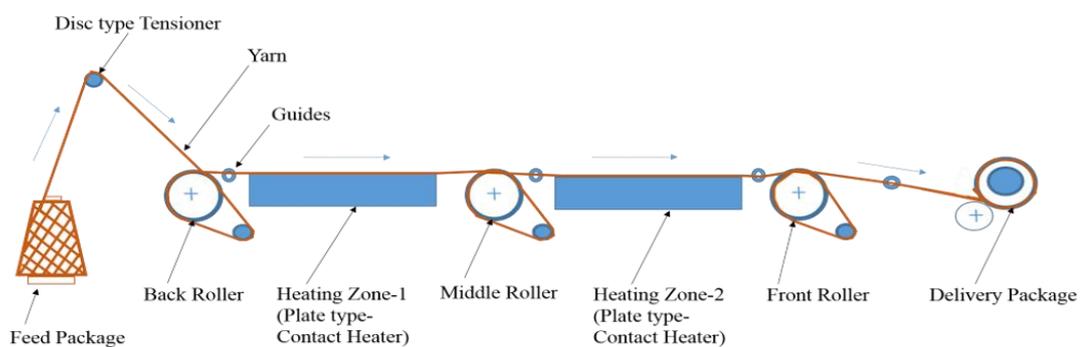
The twisted PET filaments tend to untwist, necessitating heat treatment to prevent untwisting and filament snarling. Thermal treatment was performed on yarn samples following the arrangement shown in Figure 3.7.

The DREF friction-spun core-sheath yarn is produced using AR glass, basalt, and carbon filament rovings as the core, with polypropylene (PP) as the sheath fibres. The filaments in these high-performance filament bundles have smooth surfaces, resulting in negligible frictional adhesion with the PP sheath fibres, which leads to the peeling off of the sheath fibres during the weaving process.

To stabilize the core-sheath structure, thermal treatment is applied to the core-sheath yarn (hybrid yarn or cable yarn), with the detailed process parameters listed in Table 3.5. Thermal treatment partially melts the PP sheath fibres, enhancing adhesion between the PP

sheath and the high-performance filament core. This improves yarn weavability, increases abrasion resistance during fabric formation, and prevents snarling of the twisted PET yarns.

The PET filaments wrapped around the DREF-spun core-sheath yarn structure also tend to snarl due to the torsional forces generated during the filament wrapping process. Thermal treatment structurally stabilizes the hybrid yarn, enhancing its weavability and preventing snarling. Conducted at 180–190°C, this process allows the PP fibres to partially melt and mechanically adhere to both the high-performance filament core and the PET yarn components. Despite the thermal treatment, the resulting hybrid yarn retains the necessary flexibility for weaving operations.



(a)



(b)

Figure 3.7 Thermal treatment set up used for twisted polyester and DREF spun yarn (a) schematic representation, and (b) actual machine (Heat setting machine, used for sample preparation, available in the Department of Textile and Fibre Engineering, IIT Delhi).

Table 3.5 Process parameters used in the thermal treatment operation

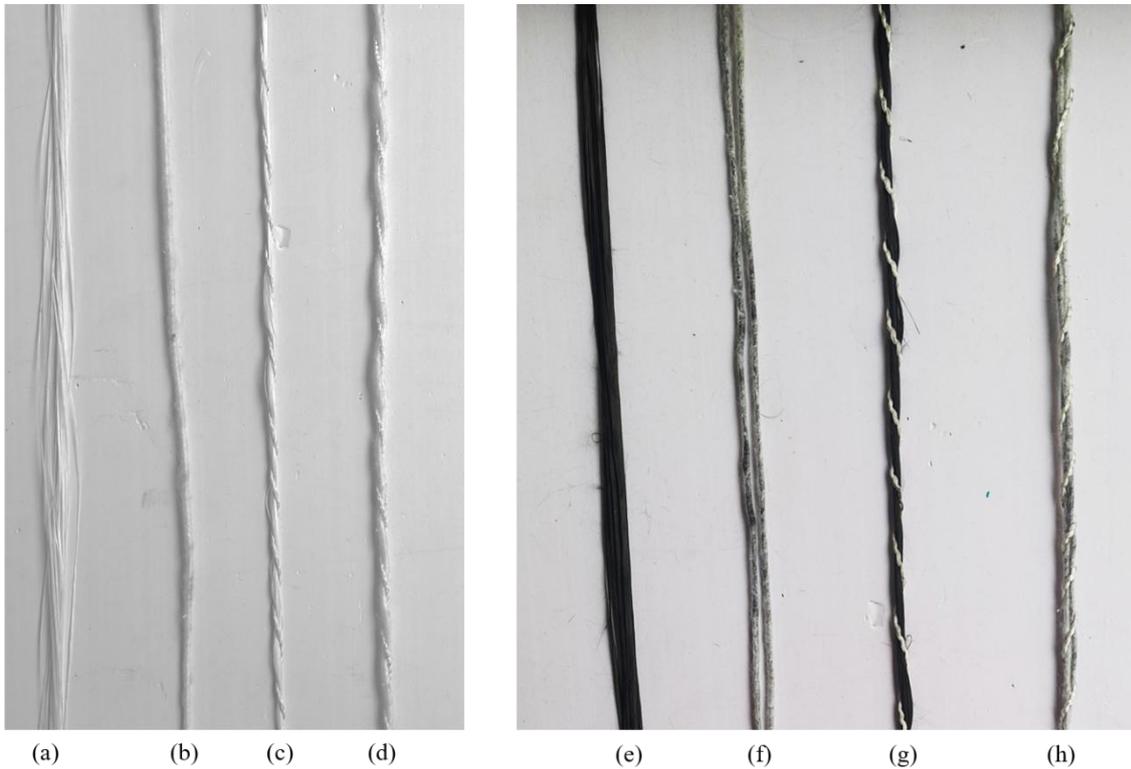
Parameters	Values
Back roller speed	10.7 rpm
Middle roller speed	10.9 rpm
Front roller speed	11.1 rpm
Temperature of heater in zone 1	180 °C
Temperature of heater in zone 2	190 °C

Figure 3.8 displays the images of parent PET yarn and modified PET yarn structures using direct twisting and braiding processes. The images of AR glass yarn and carbon parent, as well as hybrid yarn structures, are shown in Figure 3.9. Figure 3.10 depicts the basalt parent yarn and hybrid yarn structures. Additionally, Figure 3.11 shows the images of AR glass, basalt, and carbon yarn, along with their hybrid structures coated with epoxy resin. Table 3.6 presents the yarn construction details with codes for the different yarn structures used in this research work.



Different types of PET yarns: (a) Single strand of parent PET filament yarn, (b) Twisted PET yarn formed on a direct twisting machine in which a single PET yarn is helically wrapped over ten parallel assembled PET filaments (notation: 10/1_PET_T), (c) Braided PET structure formed by eight carriers each of them supplying a single PET yarn (notation: 8_PET_B).

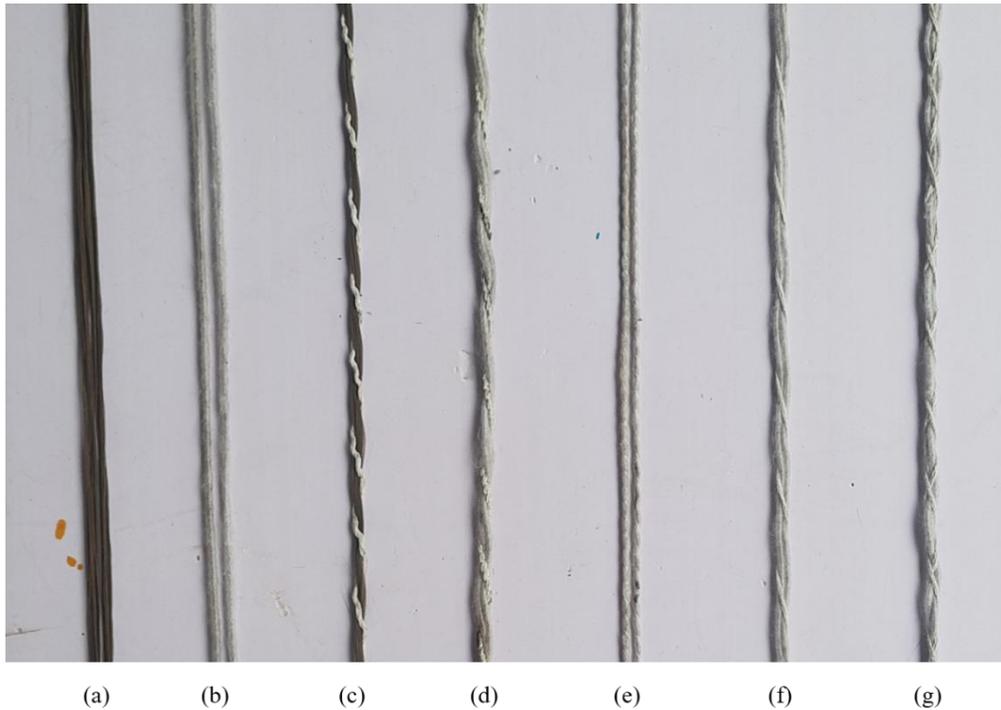
Figure 3.8 Photographs of parent PET yarn and modified PET yarn structures using twisting and braiding process.



Parent AR-glass and AR-glass-based hybrid yarn specimens without coating: (a) ARG yarn (1 strand), (b) Single strand of ARG-PP DREF spun yarn, (c) Single strand of ARG core helically wrapped by 10/1 PET yarn, (d) Single strand of ARG-PP DREF spun yarn helically wrapped by 10/1 twisted PET yarn.

Parent carbon and carbon-based hybrid yarn specimens without coating: (e) Carbon yarn (Seven strand combined), (f) carbon-PP DREF spun yarn (2 strands combined), (g) Seven strands of carbon core helically wrapped by 10/1 PET yarn, (h) Two strands of carbon-PP DREF spun yarn helically wrapped by 10/1 twisted PET yarn.

Figure 3.9 Photographs of parent AR glass yarn and AR glass-based hybrid yarn structures (left), and parent carbon yarn and carbon-based hybrid yarn structures (right) without epoxy coating.



Parent basalt and basalt-based hybrid yarn specimens without coating: (a) Basalt yarn (2 strand combined), (b) Basalt-PP DREF spun yarn (2 strand combined), (c) Two strands of basalt core helically wrapped by 10/1 PET yarn, (d) Two strands of basalt-PP DREF spun yarn helically wrapped by 10/1 twisted PET yarn, (e) Basalt-PP DREF spun yarn helically wrapped by 1 (single) PET yarn (2 strand combined), (f) Two strands of basalt-PP DREF spun yarn helically wrapped by Braided PET yarn (8 PET yarns braided together) by running a single carrier, (g) Two strands of basalt-PP DREF spun yarn helically wrapped by Braided PET yarn (8 PET yarns braided together) by running two carriers crossing each other.

Figure 3.10 Photographs of parent basalt yarn and basalt-based hybrid yarn structures without epoxy coating.



Yarn specimens coated with epoxy resin: (a) ARG-EC-Y, (b) ARG-10/1_PET_T-EC-Y, (c) ARG-PP-10/1_PET_T-EC-Y, (d) B-EC-Y, (e) B-10/1_PET_T-EC-Y, (f) B-PP-10/1_PET_T-EC-Y, (g) B-PP-8_PET_B_1S-EC-Y, (h) B-PP-8_PET_B_2S-EC-Y, (i) C-EC-Y, (j) C-10/1_PET_T-EC-Y, (k) C-PP_10/1_PET_T-EC-Y

Figure 3.11 Photographs of AR glass, basalt, and carbon yarn and their hybrid structures coated with epoxy resin.

Table 3.6 Yarn construction details with codes for different yarn structure used in this study.

Yarn code	Yarn description
ARG-Y	Parent AR Glass roving (uncoated, 2460 tex)
ARG-EC-Y	AR Glass roving coated with epoxy resin
ARG-10/1_PET_T-EC-Y	Core of AR Glass roving is helically wrapped with 10/1 twisted PET yarn and subsequently coated with epoxy resin
ARG-PP-10/1_PET_T-EC-Y	AR Glass-PP core-sheath DREF yarn is helically wrapped with 10/1 PET twisted yarn and subsequently coated with epoxy resin
B-Y	Parent Basalt roving (uncoated, 2400 tex)
B-EC-Y	Basalt roving coated with epoxy resin
B-PP-1_PET-EC-Y	Basalt-PP DREF yarn helically wrapped by a single PET yarn and subsequently coated with epoxy resin
B-10/1_PET_T-EC-Y	Core of Basalt roving is helically wrapped with 10/1 twisted PET yarn and subsequently coated with epoxy resin
B-PP-10/1_PET_T-EC-Y	Basalt-PP core-sheath DREF yarn is helically wrapped with 10/1 twisted PET yarn and subsequently coated with epoxy resin
B-PP-8_PET_B_1S-EC-Y	Basalt-PP core-sheath DREF yarn is helically wrapped with braided structure (comprising 8 PET yarns) on one side, using one carrier in the braiding operation, and is subsequently coated with epoxy resin
B-PP-8_PET_B_2S-EC-Y	Basalt-PP core-sheath DREF yarn is helically wrapped with braided structure (comprising 8 PET yarns) on both sides, crossing each other using two carrier in the braiding operation, and is subsequently coated with epoxy resin
C-Y	Parent Carbon roving (uncoated, 2520 tex)
C-EC-Y	Carbon roving coated with epoxy resin

C-10/1_PET_T-EC-Y	Core of Carbon roving is helically wrapped with 10/1 twisted PET yarn and subsequently coated with epoxy resin
C-PP_10/1_PET_T-EC-Y	Carbon-PP core-sheath DREF yarn is helically wrapped with 10/1 PET twisted yarn and subsequently coated with epoxy resin

3.3 Development of plain-woven Scrim fabric structures

Scrim fabric is desired for reinforcement in concrete, as it allows the passing of the cementitious matrix between the grid openings. This capability facilitates the formation of good mechanical anchorage, which is essential in FRCM systems. In this study, plain woven fabric with an open-grid structure (scrim fabric) was initially produced using various yarns on a manually operated handloom (Figure 3.12).

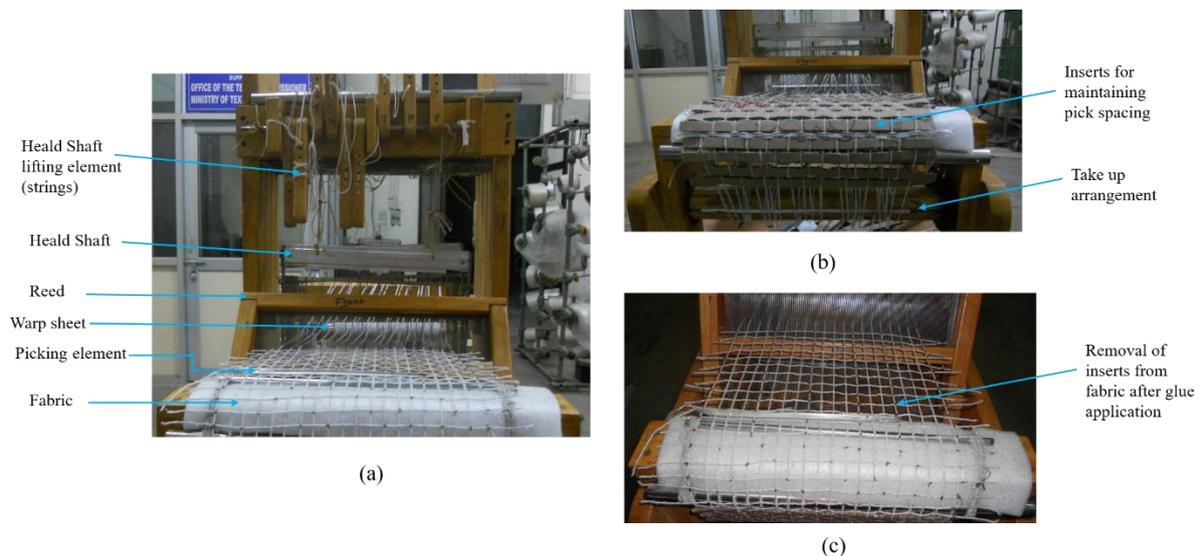


Figure 3.12 Scrim (open mesh) fabric formation using Handloom.

Different fabric samples could be produced with variable grid opening sizes (thread density). To maintain uniform grid spacing, flexible inserts were used between two consecutive picks during weaving, and the interlacement points (spots) were glued with a small amount (2-3 drops) of quick-fix glue to prevent fabric distortion. The inserts were removed afterward upon completion of the weaving process. The reason for choosing a handloom over power-operated looms was that due to high beat-up forces in power looms, the pick was laid just next to the previously inserted pick; therefore, it was not possible to

form an open mesh (scrim) type fabric with sufficient yarn spacing between subsequent yarns using a power loom.

Furthermore, it was observed that the woven fabric lacked dimensional stability after removal from the loom, as it distorted during handling, which made epoxy resin coating challenging. Hence, a new hand-operated weaving setup was devised in which iron nails were fixed and positioned at equal distances (based on the desired yarn spacing requirement) in a rectangular wooden frame as shown in Figure 3.13.

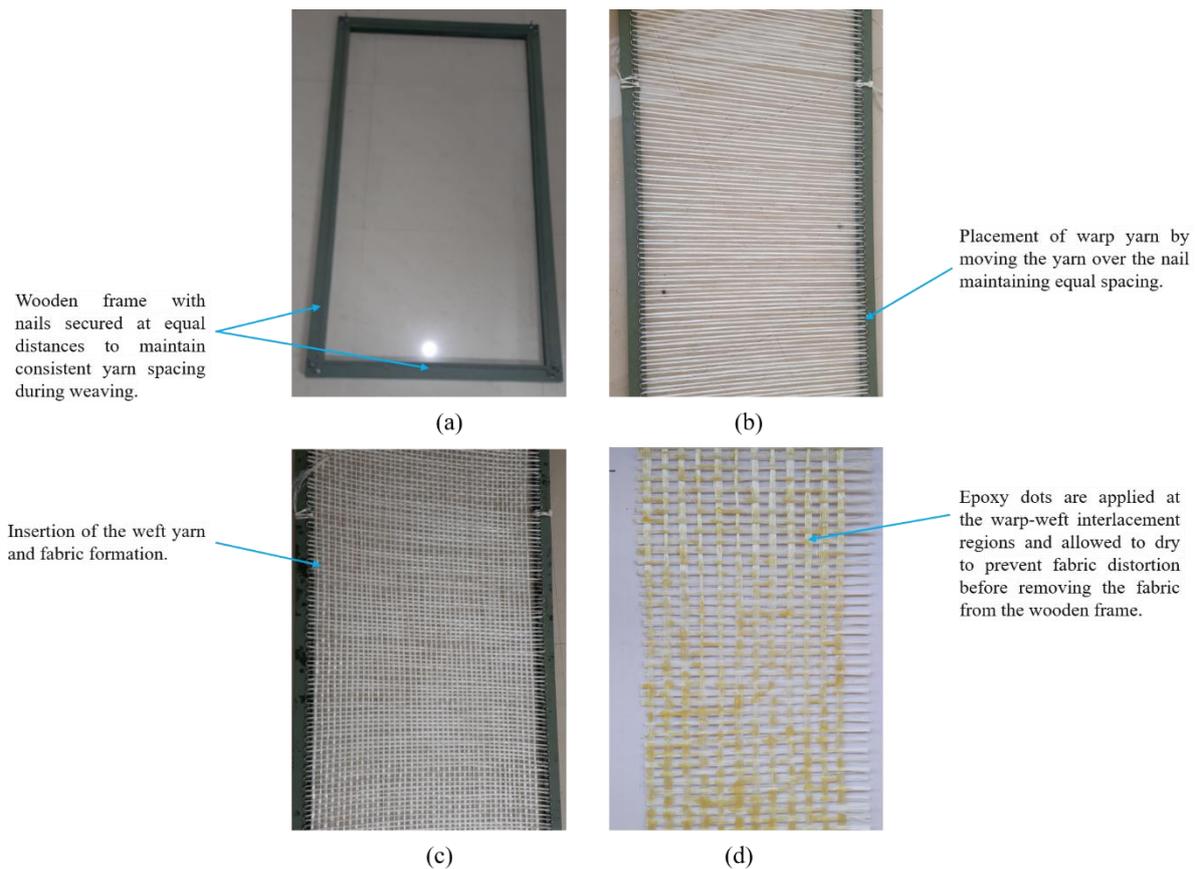
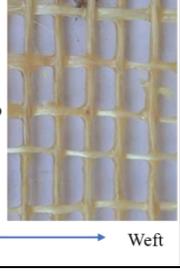


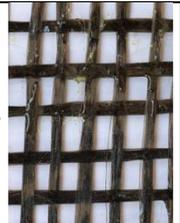
Figure 3.13 Simple hand-operated fabric weaving mechanism for producing open mesh fabric: (a) Wooden frame with nails placed at equal distances, (b) Placement of warp yarn (AR glass) in the frame, (c) insertion of weft yarn and fabric formation, (d) AR glass fabric with epoxy dots at warp-weft interlacement regions to prevent fabric distortion after its removal from the wooden frame.

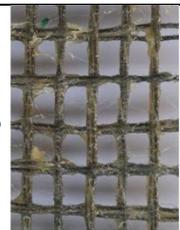
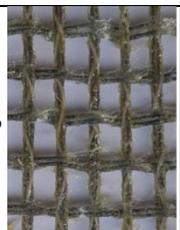
One set of yarn (warp) was first laid passing through the nails and manually stretched to avoid slackness in warp yarn. Afterwards, the weft was inserted, followed by manual stretching. Special care is taken during fabric manufacturing to ensure the warp yarns are straight and taut, with crimp handled by the weft yarns. This setup ensures the warp yarns

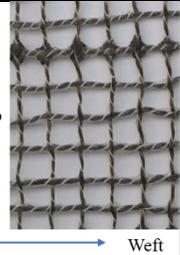
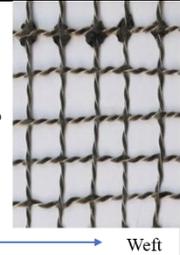
bear the tensile load during uniaxial tensile testing. Once the fabric was woven in the setup, resin coating was carried out with a brush and roller (hand layup method) and allowed to cure before cutting and removal of the fabric specimen. This allowed the formation of a coated fabric with uniformly placed warp and weft without distortion. The details of the different fabrics used in this study, including their construction details, are outlined in Table 3.7.

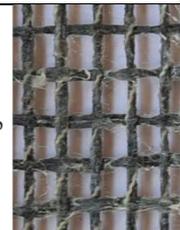
Table 3.7 Fabric construction details of various fabrics used in this study.

Fabric image	Fabric type with mesh opening size	Warp yarn description	Weft yarn description	Fabric resin coating	Fabric Code	Fabric GSM (g/m ²)
	AR Glass fabric (10mm x 12mm)	AR Glass Roving (2460 tex)	AR Glass Roving (2460 tex)	No coating is applied; only 2-3 drops of epoxy resin are used at the interlacement points to maintain fabric structural stability.	ARG-F	625
	AR Glass fabric Epoxy Coated (10mm x 12mm)	AR Glass Roving (2460 tex)	AR Glass Roving (2460 tex)	Fabric is coated with epoxy resin.	ARG-EC-F	740
	AR Glass-10/1_PET_T fabric Epoxy Coated (10mm x 12mm)	Core of AR Glass Roving is helically wrapped with 10/1 twisted PET yarn	AR Glass Roving (2460 tex)	Fabric is coated with epoxy resin.	ARG-10/1_PET_T-EC-F	1225

 <p>Warp Weft</p>	<p>AR Glass-PP-10/1_PET_T fabric Epoxy Coated (10mm x 12mm)</p>	<p>Core of AR Glass-PP DREF yarn is helically wrapped with 10/1 PET twisted yarn</p>	<p>AR Glass-PP DREF yarn</p>	<p>Fabric is coated with epoxy resin.</p>	<p>ARG-PP-10/1_PET_T-EC-F</p>	<p>1382</p>
 <p>Warp Weft</p>	<p>Basalt fabric (10mm x 12mm)</p>	<p>Basalt Roving (2400 tex)</p>	<p>Basalt Roving (2400 tex)</p>	<p>No coating is applied; only 2-3 drops of epoxy resin are used at the interlacement points to maintain fabric structural stability.</p>	<p>B-F</p>	<p>543</p>
 <p>Warp Weft</p>	<p>Basalt fabric Epoxy Coated (10mm x 12mm)</p>	<p>Basalt Roving (2400 tex)</p>	<p>Basalt Roving (2400 tex)</p>	<p>Fabric is coated with epoxy resin.</p>	<p>B-EC-F</p>	<p>726</p>
 <p>Warp Weft</p>	<p>Basalt-10/1_PET_T fabric Epoxy Coated (10mm x 12mm)</p>	<p>Core of Basalt Roving is helically wrapped with 10/1 PET twisted yarn</p>	<p>Basalt Roving (2400 tex)</p>	<p>Fabric is coated with epoxy resin.</p>	<p>B-10/1_PET_T-EC-F</p>	<p>1105</p>

	<p>Basalt-PP-10/1_PET_T fabric Epoxy Coated (10mm x 12mm)</p>	<p>Core of Basalt-PP DREF yarn is helically wrapped by a 10/1 PET twisted yarn</p>	<p>Basalt-PP DREF yarn</p>	<p>Fabric is coated with epoxy resin.</p>	<p>B-PP-10/1_PET_T-EC-F</p>	<p>1225</p>
	<p>Basalt-PP-1_PET fabric Epoxy coated (10mm x 12mm)</p>	<p>Core of Basalt-PP DREF yarn helically wrapped by a single PET yarn</p>	<p>Core of Basalt-PP DREF yarn helically wrapped by a single PET yarn</p>	<p>Fabric is coated with epoxy resin.</p>	<p>B-PP-1_PET-EC-F</p>	<p>882</p>
	<p>Basalt-PP-8_PET_B_1S fabric Epoxy Coated (10mm x 12mm)</p>	<p>Initially, a braided PET strand, consisting of eight PET yarns, is formed on a braiding machine. This braided PET strand is then helically wrapped over the Basalt-PP DREF yarn (core strand) on one side using a single carrier in the braiding operation.</p>	<p>Basalt-PP DREF yarn</p>	<p>Fabric is coated with epoxy resin.</p>	<p>B-PP-8_PET_B_1S-EC-F</p>	<p>1380</p>
	<p>Basalt-PP-8_PET_B_2S fabric Epoxy Coated (10mm x 12mm)</p>	<p>Initially, a braided PET strand, consisting of eight PET yarns, is formed on a braiding machine. This braided PET strand is then helically wrapped over the Basalt-PP DREF yarn (core strand) on two sides using two carriers in the braiding operation, crossing each other.</p>	<p>Basalt-PP DREF yarn</p>	<p>Fabric is coated with epoxy resin.</p>	<p>B-PP-8_PET_B_2S-EC-F</p>	<p>1440</p>

	<p>Basalt-PP-1_PET_TP fabric composite (6mm x 7mm)</p>	<p>Core of Basalt-PP DREF yarn is helically wrapped by a single PET yarn</p>	<p>Core of Basalt-PP DREF yarn is helically wrapped by a single PET yarn</p>	<p>No coating is applied; the fabric is processed in compression moulding to form a thermoplastic composite by melting to allow compaction and consolidation of sheath PP fibres.</p>	<p>B-PP-1_PET_TP-F (6 mm x 7 mm)</p>	<p>390</p>
	<p>Basalt-PP-PET TP fabric composite (10mm x 12mm)</p>	<p>Core of Basalt-PP DREF yarn is helically wrapped by a single PET yarn</p>	<p>Core of Basalt-PP DREF yarn is helically wrapped by a single PET yarn</p>	<p>No coating is applied; the material is processed in compression moulding to form a thermoplastic composite by melting to allow compaction and consolidation of sheath PP fibres.</p>	<p>B-PP-1_PET_TP-F (10 mm x 12 mm)</p>	<p>320</p>
	<p>Carbon fabric (10mm x 12mm)</p>	<p>Carbon Roving (tow) (2520 tex)</p>	<p>Carbon Roving (tow) (2520 tex)</p>	<p>No coating is applied; only 2-3 drops of epoxy resin are used at the interlacement points to maintain fabric structural stability.</p>	<p>C-F</p>	<p>702</p>
	<p>Carbon fabric Epoxy Coated (10mm x 12mm)</p>	<p>Carbon Roving (tow) (2520 tex)</p>	<p>Carbon Roving (tow) (2520 tex)</p>	<p>Fabric is coated with epoxy resin.</p>	<p>C-EC-F</p>	<p>972</p>

 <p>Warp</p> <p>Weft</p>	<p>Carbon-10/1_PET_T fabric Epoxy Coated (10mm x 12mm)</p>	<p>Core of CarbonRoving is helically wrapped by a 10/1 PET twisted yarn</p>	<p>Carbon Roving (tow) (2520 tex)</p>	<p>Fabric is coated with epoxy resin.</p>	<p>C-10/1_PET_T-EC-F</p>	<p>1323</p>
 <p>Warp</p> <p>Weft</p>	<p>Carbon-PP-10/1_PET_T fabric Epoxy Coated (10mm x 12mm)</p>	<p>Core of Carbon-PP DREF yarn is helically wrapped by a 10/1 PET twisted yarn</p>	<p>Carbon-PP DREF yarn</p>	<p>Fabric is coated with epoxy resin.</p>	<p>C-PP-10/1_PET_T-EC-F</p>	<p>1435</p>

3.4 Fabrication of fabric composites

3.4.1 Production of thermoplastic fabric composite using the compression moulding process

The fabric structures made from hybrid yarns with a basalt core, covered with sheath of PP fibres, and a single PET yarn is helically wrapped on the strand (B-PP-1_PET_TP-F) in two different mesh openings (10 mm x 12 mm and 6 mm x 7 mm) were processed using a compression moulding machine (SANTEC make) to form thermoplastic fabric composites. The PP fibres melt completely and are expected to bind the reinforcing basalt (BR) filaments, thereby enhancing the mechanical properties of the composite. The composites were produced for woven fabric samples based on hybrid yarn (B-PP-1_PET) using the compression moulding machine. The process parameters for the compression moulding operation were a temperature of 190°C, a breathing pressure of 8 bar, a curing pressure of 20 bar, and a curing time of 5 minutes.

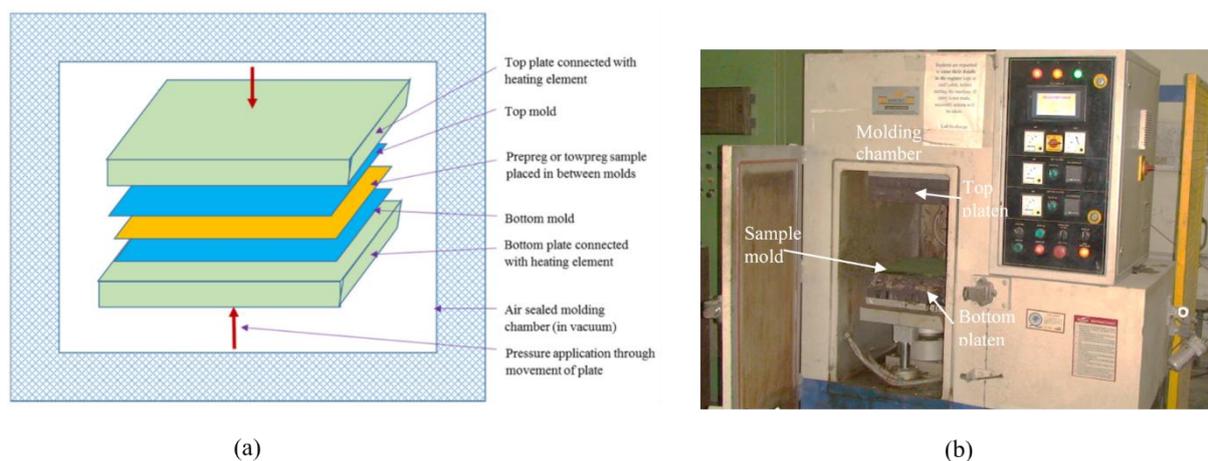


Figure 3.14 Compression moulding: (a) schematic representation, (b) actual machine (Machine make: SANTEC, used for sample preparation, available in the Department of Textile and Fibre Engineering, IIT Delhi).

3.4.2 Production of thermoset fabric composites via epoxy resin coating

The epoxy resin is mixed with the hardener in a weight proportion of 100:12 (epoxy to hardener ratio). It is uniformly mixed for 10 minutes before being applied to the fabric specimen using a brush and roller (hand layup). The resin-coated fabric is initially exposed to a convection heating setup for 2 hours, followed by room temperature curing for 8 hours before the fabric is removed from the handloom setup.

3.5 Cross-section examination of yarn samples

3.5.1 Preparation of yarn samples for cross-section examination

For specimen preparation, small flexible silicon hollow cylindrical moulds with sealed bottoms were used, and yarn samples were placed in a straight configuration at the centre of the container. The epoxy-hardener homogeneous mix (epoxy/hardener = 100/12 wt. proportion) was poured slowly along the side walls of the moulds to avoid air entrapment. The specimens were allowed to cure for 12 hours, followed by heat treatment at 70°C for 2 hours to ensure proper hardening of the epoxy resin. Subsequently, a sample polishing machine (Make: Metatech, Model: Metapol DC-II) was used for polishing the specimens (Figure 3.15). Different grades of emery paper are used for sample polishing, starting from coarse to fine grit sizes. The polishing process is performed with a continuous water supply to prevent overheating of the epoxy blocks, and the final polish is achieved on a velvet cloth.



Figure 3.15 Sample polishing machine (Make: Metatech, Model: Metapol DC-II used for specimen polishing, available in the Department of Textile and Fibre Engineering, IIT Delhi).

3.5.2 Microscopic examination of yarn cross-sections

Micrographs of the polished specimens were obtained using a microscope equipped with a camera and image processing software (Figure 3.16). The software tool facilitated easy measurement of the areas of different cross-sectional shapes of the specimens. These cross-sectional area values are essential for calculating the tensile stress of the yarn, fabric, and composites.

The cross-sectional shape of fibres significantly affects their surface geometry and various properties, including lustre, softness, friction, comfort, dyeing, pilling, bulkiness, and fabric mechanical properties such as bending rigidity[147], [148]. The shape factor, a

geometric parameter also known as the non-roundness factor, measures deviation from a circular cross-section. A value of 1 (one) indicates a perfectly round shape, while higher values denote greater deviation[147]. Singh and Behera (2021) highlighted that the influence of fibre cross-section extends from yarn to fabric[148]. Various methods, including those by Hearle(2008) [149], Neckar (1998)[150], and Bueno et al. (2004)[151], are available to measure the shape factor. In this study, the concept of fibre shape factor was applied to the yarn structure, and the non-roundness factor (shape factor) of different yarn specimens was calculated using Bueno et al.'s equation [151]to assess its effect on the mechanical properties of fabric and FRCM specimens.

$$k = \frac{C_f}{2\sqrt{\pi S}} \dots Eq. (2)$$

Where; k is the non-roundness factor (shape factor) of yarn specimen (dimensionless); C_f is the yarn perimeter (mm); S is the cross-sectional area of the yarn specimen (mm²).

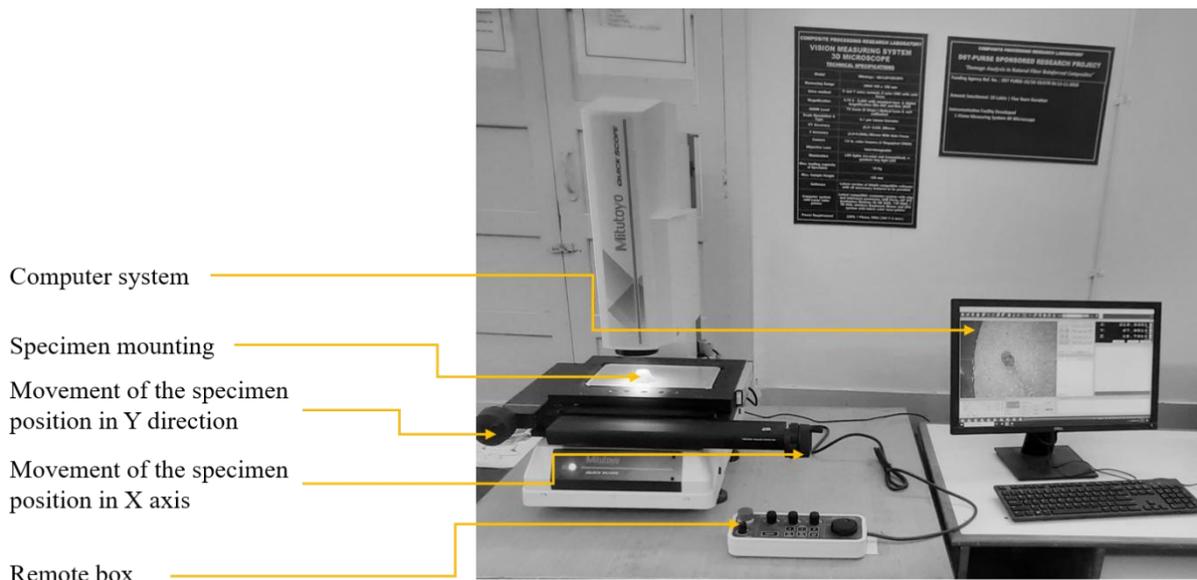


Figure 3.16 Microscope for examining and capturing yarn cross-sectional images (Mitutoyo-QS-L2010Z/AFC used for obtaining specimen micrographs, available in the Composite Lab, Department of Mechanical Engineering, FTE).

3.6 Mortar mix design and fabrication of unreinforced, yarn-reinforced, and fabric-reinforced mortar specimens for mechanical testing

3.6.1 Fabrication of formwork for casting mortar specimens for pull-out, tensile and flexural test

The formwork is fabricated using wooden materials, with the base plate made from PVC sheet, as illustrated in Figure 3.17.

It is designed to accommodate the casting of concrete specimens with dimensions of 15 mm (thickness) × 60 mm (width) × 500 mm (length) for pull-out and uniaxial tensile test specimens, and 30 mm (thickness/depth) × 100 mm (width) × 500 mm (length) for flexural test specimens. Multiple formworks are fabricated to enable the simultaneous casting of multiple tensile and flexural concrete specimens, ensuring uniform consistency in the matrix.

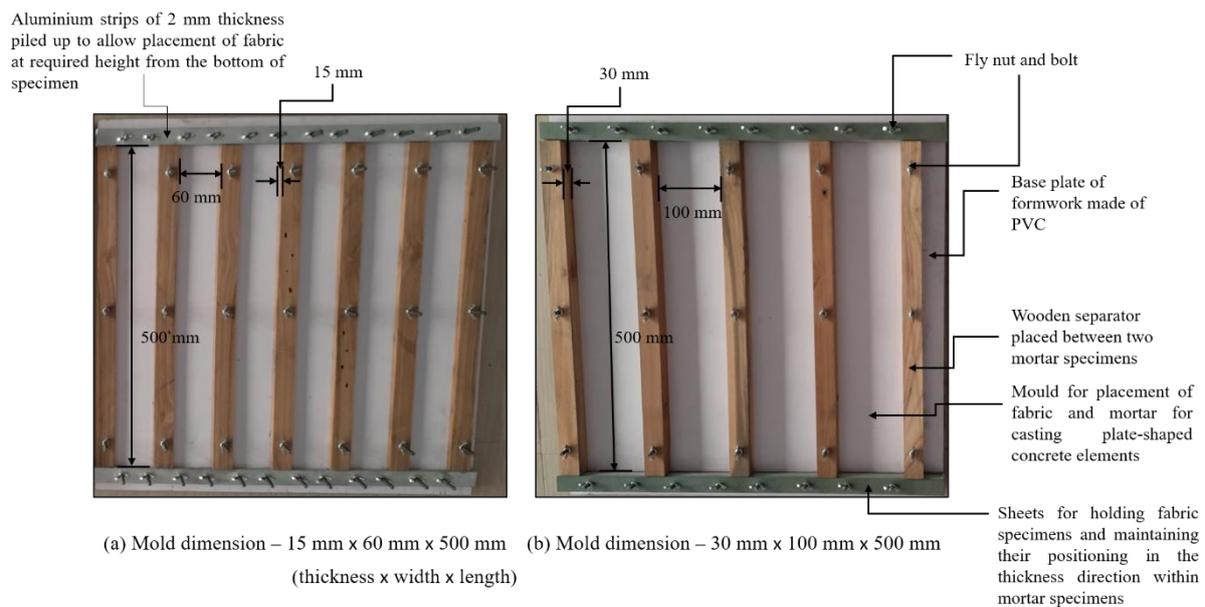


Figure 3.17 Fabricated moulds for casting FRCM specimens for investigating: (a) tensile and pull-out behaviour, (b) flexural behaviour.

3.6.2 Formulation of mortar mix proportions

Fine-grained mortar is recommended for FRCM specimens, with the maximum size of fine aggregate restricted to 2.36 mm, which is 3 – 4 times smaller than the grid size (10 mm x 12 mm) selected for fabric specimens. Limiting the aggregate size facilitates easier flow and penetration of mortar into the openings of fabric-reinforced specimens, thereby enhancing fibre-mortar bonding. The cementitious mortar is prepared using binders (OPC 53, fly ash,

ground granulated blast furnace slag, and silica fume), fine aggregate (river sand and crushed stone), water, and superplasticizer. Supplementary Cementitious Materials (pozzolanic materials) such as fly ash, GGBS, and silica fume are used to replace OPC binder in the cementitious mortar. These pozzolanic materials improve the mechanical properties and durability of concrete while offering a lower carbon footprint, making them sustainable alternatives to OPC. Additionally, the addition of polypropylene fibres in limited quantities has been found to prevent plastic shrinkage and improve tensile properties. Initially, experimental studies from literature were reviewed, and mix proportion trials were conducted, including a slump test, before finalizing the mortar mix proportions for this study. The mix proportions of mortar ingredients by weight ratio used for FRCM preparation is listed in Table 3.8.

Table 3.8 Mix proportions of mortar ingredients by weight ratio for FRCM preparation.

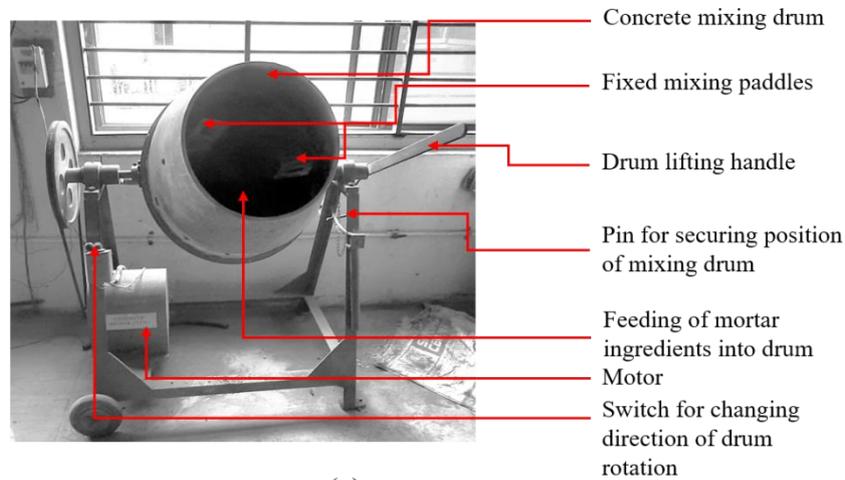
Mortar ingredients	Weight of ingredients in Kilograms (kgs)
Cement (OPC 53)	498
Fly ash	49.8 (10% cement by weight)
Ultrafine Ground granulated blast furnace slag (GGBFS)	49.8 (10% cement by weight)
Silica fume (SF)	49.8 (10% cement by weight)
Water	194.2 (water/binder = 0.3)
Fine aggregate (sand)	600
Fine aggregate (crushed stone)	600
Polycarboxylate ether (PCE) based Superplasticizer (SP)	7.8 (1.2% solid/binder by weight)
Polypropylene (PP) fibre	5.13

3.6.3 Mortar mixing, casting and curing of mortar specimens

Mortar mixing was carried out in motor operated rotary drum mixer machine (Figure 3.18) in which all the mortar ingredients are added as per the weighted mix proportions.

Initially the river sand and crushed stone (fine aggregates) are fed and allowed to mix for 5 minutes in both clockwise and anticlockwise direction. This is followed by addition of OPC, silica fume, fly ash and GGBS and again mix for another 5 minutes. The water and superplasticizer are added slowly while the mixer machine is in rotation. Finally, the opened

PP fibres are added by slowly dispersing in the mortar and then the whole mix is allowed to mix for 20-25 minutes in both clockwise and anticlockwise direction until good flowability of cementitious mortar is achieved.



(a)



(b)



(c)



(d)

Figure 3.18 Mortar mixing: (a) Concrete mixer, (b) dry mixing of mortar ingredients, (c) addition of water and superplasticizer to the mortar mix, (d) mixing alternately in clockwise and anti-clockwise direction for 20-25 minutes to achieve good flowability of the mortar.

The casting of PP fibre reinforced mortar cubes of dimension 150 mm x 150 mm x 150 mm (confirming to IS 1199 (Part 5): 2018) was done for finding out the compressive strength of the mortar cubes[152]. Similarly, the cylindrical mortar specimens of dimension 150 mm diameter and 300 mm height were casted (confirming to IS 1199 (Part 5): 2018) for finding out the split tensile strength of the mortar cylinders[152]. The mortar specimen casting and curing procedure is shown in Figure 3.19.

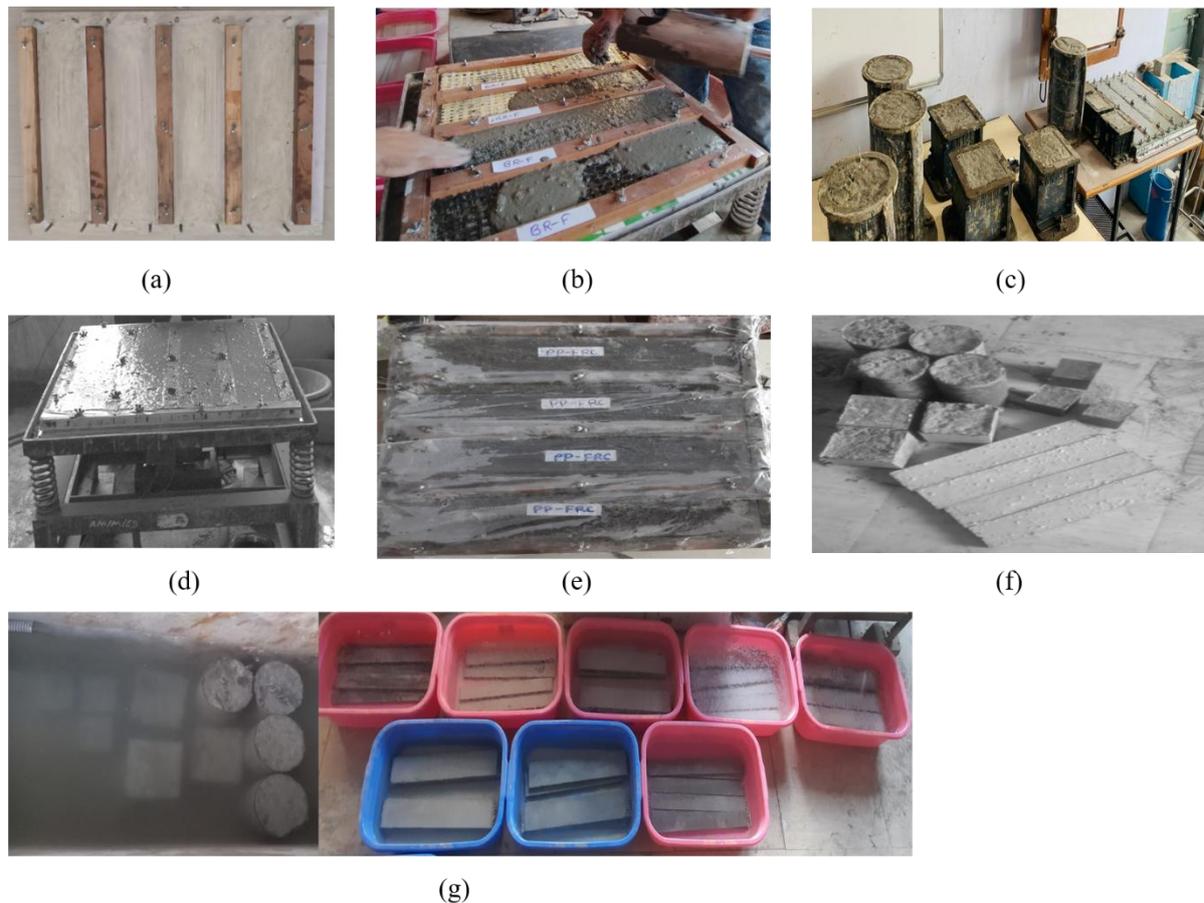


Figure 3.19 Casting of FRCM specimens: (a) Application of oil for easy release of concrete specimens from the mould during demoulding, (b) Placement of fabric layers in formwork followed by pouring of mortar, (c) Casting of cube, cylinder, and plate specimens, (d) Placing the mortar-filled mould on a vibrating table for proper compaction, (e) Covering the mortar-filled mould with a thin plastic sheet to prevent moisture loss and shrinkage, (f) Demoulding of concrete specimens from moulds after 24 hours of casting, (g) Placing concrete specimens in a water bath for curing.

3.6.4 Mortar specimen compaction and curing

During the mortar filling process, the formwork is placed on a vibrating table for about 5 minutes to ensure proper distribution and compaction of the mortar. Once proper compaction is achieved, the formwork is removed from the vibrating table and wrapped with a thin plastic film to prevent water loss. The mortar specimens are allowed to cure for 24 hours in the mould before being demoulded and then immersed in a water tub for 27 days for curing (Figure 3.19). After 27 days, the mortar specimens are removed from the water bath, and various tests (pull-out, tensile, and flexural) are performed.

3.6.5 Slump test for mortar consistency

To assess the workability of the mortar mix, a slump test was conducted in accordance with IS 1199 (Part 2): 2018[153]. This method employs a frustum-shaped mould with dimensions of 100 mm diameter at the top, 200 mm diameter at the base, and a height of 300 mm. The mould is positioned on a steel base plate, and the mortar mix is poured into it in three layers. Each layer is compacted by tamping the rod 25 times before pouring the next layer. Upon completion, the mould is lifted vertically within 5 ± 2 seconds. The slump height (h) is then determined as the difference between the height of the mould and the highest point of the mortar. The slump test procedure followed is shown in Figure 3.20. For the mortar mix design considered in this study (Section 3.6.1), the slump height was found to be 250 mm.



Figure 3.20 Slump test of mortar: (a) Oiling the frustum-shaped mould and placing it in the centre of a base steel plate, (b) Pouring mortar into the mould in three layers and compacting each layer by tamping with a rod while holding the mould, (c) Filled mould, (d) Vertical lifting of the mould, (e) Measuring slump height (the difference between the height of

the mould and the highest point of the mortar), (f) Observing the flow of mortar on the base steel plate.

3.6.6 Preparation of YRCM specimens for yarn pull-out testing

For the yarn pull-out test from yarn-reinforced cementitious mortar (YRCM) specimen, a single yarn (uncoated or resin-coated) is centrally positioned in the formwork's width and thickness. The yarn is manually stretched at both ends to make it straight and taut before filling the formwork with mortar.

3.6.7 Preparation of FRCM specimens for yarn pull-out testing

For the yarn pull-out test from fabric-reinforced cementitious mortar (FRCM) specimen, a single layer of fabric (either uncoated or resin-coated) is placed and aligned in the centre of the formwork in the thickness direction. The fabric is manually stretched at both ends to make it straight and taut before filling the formwork with mortar (Figure 3.21, a).

3.6.8 Preparation of FRCM specimens for uniaxial tensile testing

For the uniaxial tensile test from fabric-reinforced mortar, two layers of fabric (either uncoated or resin-coated) are placed. The first layer is positioned 3 mm from the bottom of the formwork, with a 2 mm gap between the two layers. The fabric layers are manually stretched at both ends to make it straight and taut before filling the formwork with mortar (Figure 3.21, b).

3.6.9 Preparation of FRCM specimens for flexural testing

For the flexural test of fabric-reinforced mortar, three layers of fabric (either uncoated or resin-coated) are used. The first layer is positioned 5 mm above the bottom of the formwork, followed by the second and third layers, with a 2 mm gap between each fabric layer. The fabric layers are manually stretched at both ends to make it straight and taut before filling the formwork with mortar (Figure 3.21, c).

3.7 Tensile testing method for yarn, fabric, and fabric composite specimens

The tensile test of yarn, fabric, and fabric composite specimens was conducted using the Shimadzu UTM AG-X plus with a 100 kN capacity, at a gauge length of 150 mm (250 mm effective length), and a test speed of 2 mm/min, following ASTM standards D3039/D3039M – 17, D4018 – 23, and D2343 – 17[154]–[156]. The low-test speed was chosen in

consideration of the uniaxial tensile test of the fabric-reinforced concrete specimens, which were also tested at a low speed (1 mm/min) (Figure 3.22). Before testing, the ends of the yarn and fabric specimens were tabbed (glued using epoxy) with a tabbing material (aluminium sheet 1.5 mm thick) to avoid stress concentration in the jaw portion of the specimen. Five samples were tested for each specimen. For fabric composite specimens, the specimen width was maintained at 40 mm.

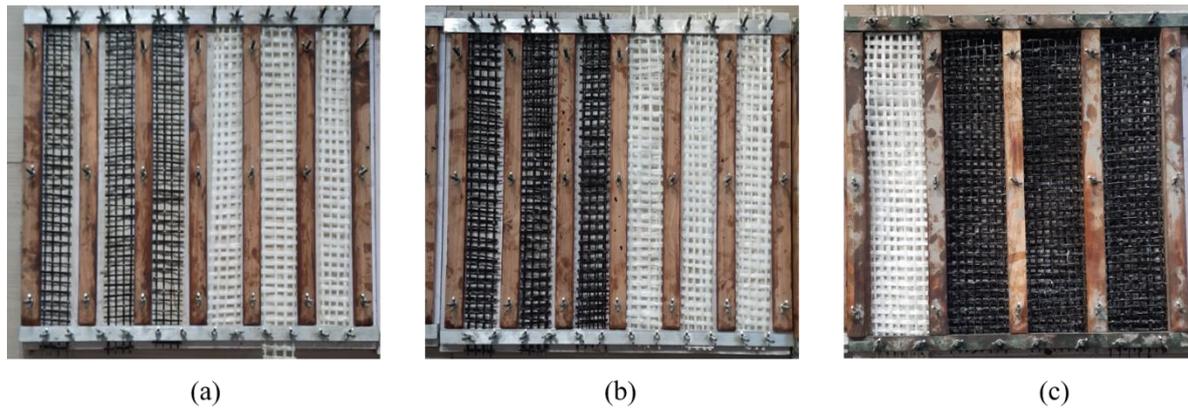


Figure 3.21 Formwork for casting plate specimen with: (a) one layer of fabric for pull-out test specimens, (b) two layers of fabric for uniaxial tensile test specimens, (c) three layers of fabric for flexural test specimens.

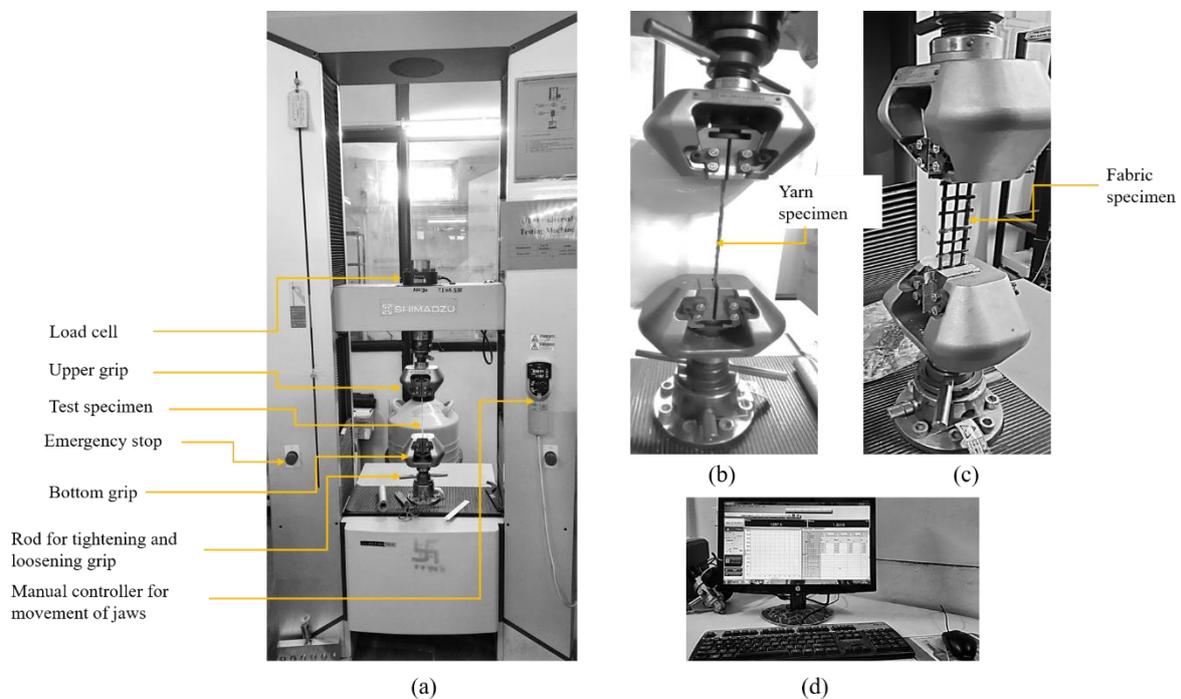


Figure 3.22 Test specimen configuration for tensile test of yarn and fabric specimens: (a) actual machine, (b) yarn specimen gripped in machine jaws, (c) fabric specimen gripped in

machine jaws, and (d) computer with graphical analysis (Shimadzu UTM AG-X plus, used for yarn and fabric specimen testing, available in the Department of Textile Engineering, FTE).

3.8 Compression strength testing method for mortar cube specimens

The compression test of the mortar cubes (150 mm x 150 mm x 150 mm) was conducted 28 days after casting, using a 100-tonne capacity universal testing machine (UTM) in accordance with IS 516 (Part 1/Sec 1): 2021[157]. The cube specimens were positioned in the centre of the machine, ensuring that the load was applied to the two cast parallel surfaces of the cubes, as shown in Figure 3.23 (a).

The compressive strength of the specimen is calculated using the following equation:

$$\sigma_c = \frac{P}{A_c} \dots Eq. (3)$$

Where, σ_c = compressive strength of specimen in MPa; P = maximum load in N; and A_c = cross-sectional area of the mortar cube specimen in mm^2 .

3.9 Split tensile testing method for mortar cylinder specimens

The split tensile test of the mortar cylinders (150 mm in diameter and 300 mm in height) was conducted 28 days after casting, using a 100-tonne capacity UTM in accordance with IS 516 (Part 1/Sec 1): 2021[157]. This test measures the split tensile strength by applying a compressive force to the cylindrical specimen, which is placed horizontally between the upper and lower plates of the UTM, as shown in Figure 3.23 (b).

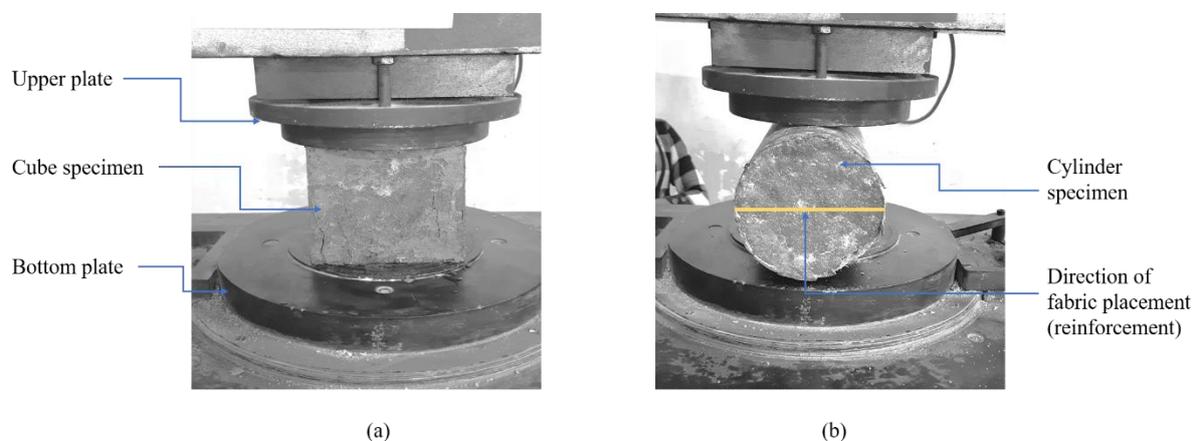


Figure 3.23 Test specimen configuration for (a) compression test of cube specimens, (b) split tensile test of cylinder specimens (UTM, used for specimen testing, available in the Department of Applied Mechanics, FTE).

The splitting tensile strength of the cylinder specimen is calculated using the following equation:

$$f_{st} = \frac{2P}{\pi ld} \dots Eq. (4)$$

Where, σ_{st} = split tensile strength of specimen in MPa; P = maximum load in N; l = length of the mortar cylinder specimen in mm, and d = diameter of the mortar cylinder specimen in mm.

3.10 Yarn pull-out testing method for YRCM and FRCM specimens

The pull-out test setup and specimen configuration used in this study were designed based on the double-sided unsymmetrical test methodologies by Lorenz & Ortlepp, Tekle et al., and Portal et al. [158]–[160]. For the pull-out test of yarn from yarn-reinforced mortar specimens, saw cuts measuring 5 mm in thickness and 22.5 mm in length along the width of the specimen are created on both sides of the plate specimens with dimensions of 15 mm (thickness) x 60 mm (width) x 500 mm (length) without disturbing the centrally embedded yarn. Subsequently, a 15 mm hole is drilled into the plate specimen using a hollow cylindrical hollow drill, ensuring that the embedded length remains 25 mm inside the mortar specimen. Prior to cutting and drilling, proper marking of specimens is conducted, and during these operations, water is continuously supplied while careful attention is paid to prevent specimen damage.

In the pull-out test of yarn from fabric-reinforced mortar specimens, saw cuts measuring 5 mm in thickness and 22.5 mm in length along the width of the specimen are created on both sides of the plate specimens – 15 mm (thickness) x 60 mm (width) x 500 mm (length), cutting the fabric along with the mortar, while leaving the centrally located yarn intact within the fabric structure. Subsequently, a 15 mm hole is drilled into the plate specimen using a hollow cylindrical drill, ensuring that the embedded length of the yarn remains 25 mm inside the mortar specimen.

Further, the plate specimen is secured between top and bottom rubber sheets within a set of upper and lower metallic grips to prevent crushing failure during jaw tightening. These

grips are further connected to rods on both sides, held in place by machine jaws. A schematic representation of the pull-out test experimental setup is depicted in Figure 3.24. The pull-out test is conducted using a 100 kN capacity with load cell of 25 kN on a Universal Testing Machine (UTM) equipped with a Win software at a constant extension rate of 1 mm/min. The pull-out load and slip (deflection) behaviour are recorded and plotted accordingly.

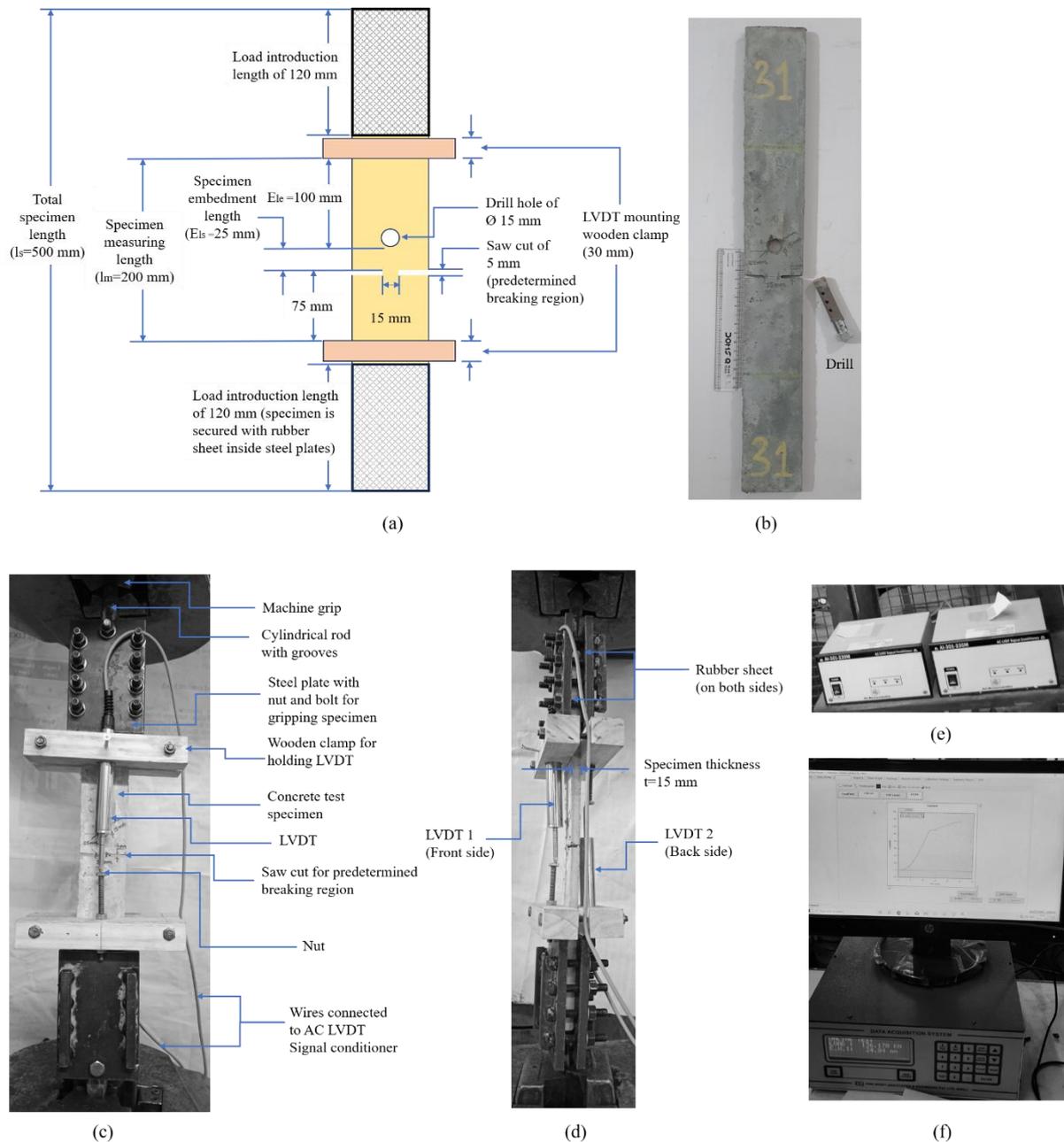


Figure 3.24 Test specimen configuration for double-sided test pull-out with unsymmetrical anchorage length: (a) schematic representation, (b) actual FRCM specimen, (c) front view of experimental set-up with LVDT, (d) side view of experimental set-up with LVDT, (e) AC LVDT signal conditioner, and (f) computer with data acquisition system (UTM equipped with

Win software, used for specimen testing, available in the Department of Applied Mechanics, FTE).

The average bond stress during pull-out test is calculated using the equation[125]:

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

Where, U_r represents the contact perimeter of the roving (yarn) as measured by a microscope, and l_e denotes the embedment length of the roving (yarn) within the cementitious matrix.

Using energy method, the energy absorbed by the specimen during pull-out test can be calculated by the area under the load-slip (load-displacement) graph using the following equation:

$$W = \int_0^{\delta} F d\delta \dots \text{Eq. (5)}$$

Where; W is the energy absorbed by the specimen (kN.mm); δ is the slip (mm); F is the pull-out load (kN).

3.11 Uniaxial tensile testing method for FRCM specimens

For the uniaxial test, the plate specimen with dimensions of 15 mm (thickness) x 60 mm (width) x 500 mm (length) is securely positioned between top and bottom rubber sheets within a set of upper and lower steel plates to prevent crushing failure during jaw tightening. These plates are further connected to rods on both sides, which are held in place by machine jaws. The uniaxial tensile test is conducted using a 100 kN capacity with load cell of 50 kN on a Universal Testing Machine (UTM) equipped with a Win software at a constant extension rate of 1 mm/min, following the guidelines of RILEM Technical Committee 232-TDT: 2016[161]. LVDTs are attached to both sides of the tensile specimen to measure displacement and are connected to an LVDT signal conditioner and data logger. A schematic representation of the experimental setup for the uniaxial tensile test is depicted in Figure 3.25. Tensile load and deflection are recorded and plotted accordingly.

The tensile strength of the specimen is calculated using the following equation:

$$\sigma_t = \frac{P}{A_c} \dots \text{Eq. (6)}$$

Where, σ_t = tensile strength of specimen in MPa; P = maximum load in N; and A_c = cross-sectional area of the plate specimen in mm^2 .

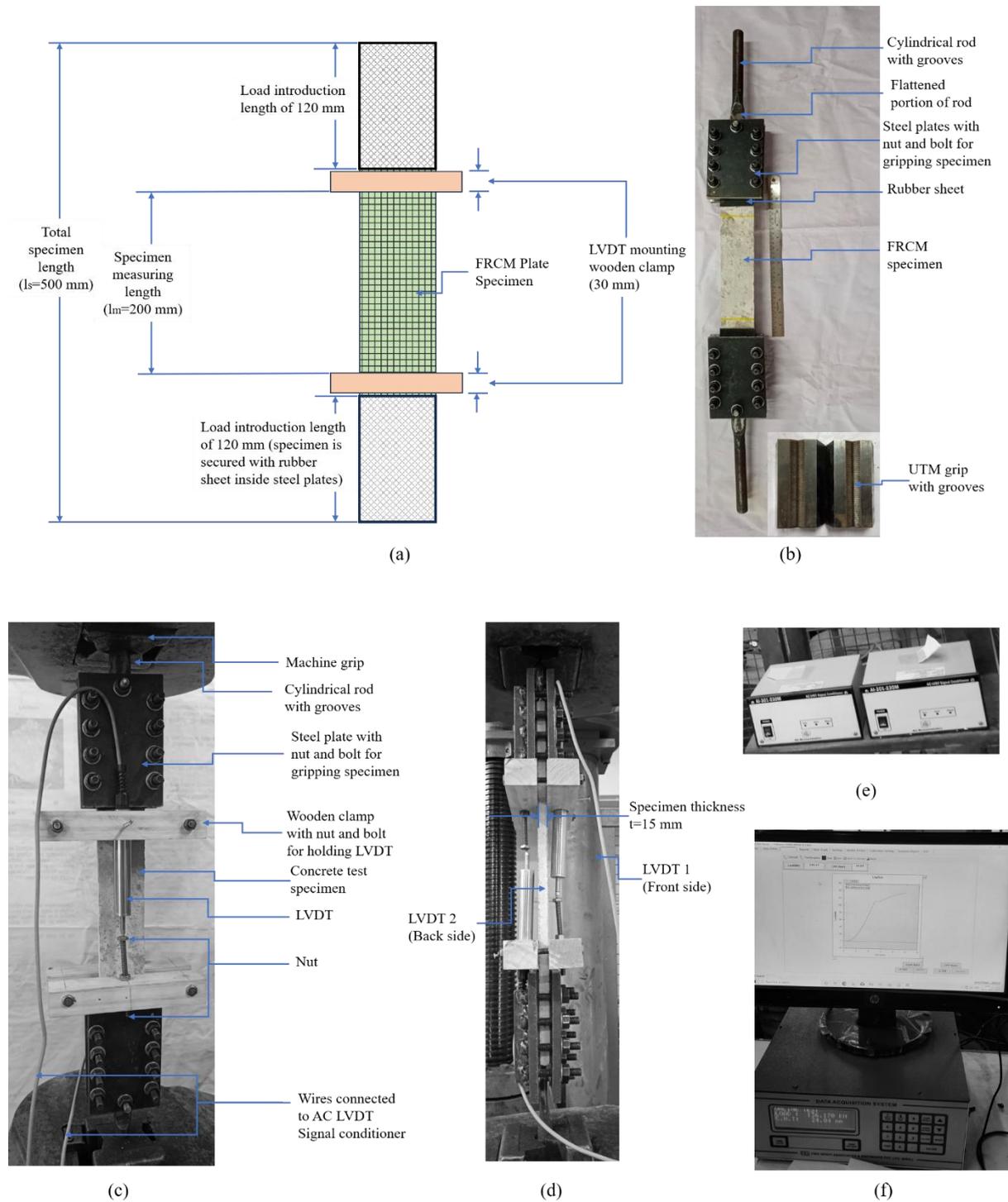


Figure 3.25 Test specimen configuration for uniaxial tensile test for FRCM specimens: (a) schematic representation, (b) actual FRCM specimen gripped inside steel plate, (c) front view of experimental set-up with LVDT, (d) side view of experimental set-up with LVDT, (e)

AC LVDT signal conditioner, and (f) computer with data acquisition system (UTM equipped with Win software, available in the Department of Applied Mechanics, FTE).

Using energy method, the energy absorbed by the FRCM specimen during tensile test can be calculated by the area under the load-displacement graph using the following equation:

$$W = \int_0^{\delta} F d\delta \dots Eq. (5)$$

Where; W is the energy absorbed by the specimen (kN.mm); δ is the displacement (mm); F is the tensile load (kN).

3.12 Flexural testing method for FRCM specimens

The specimen size for the flexural test was 30 mm (thickness/depth) x 100 mm (width) x 500 mm (length). A three-point bending test was conducted on both unreinforced and reinforced (FRCM) specimens using a universal testing machine (UTM) with a 100 kN capacity and a 50 kN load cell, equipped with Win software. The effective span length of the beam was set to 400 mm. The test was performed at a displacement rate of 1 mm/min. A digital dial gauge was positioned at the centre of the beam to measure the midspan deflection of the plate specimen. A schematic representation of the flexural test experimental setup is shown in Figure 3.26.

The flexural strength of the plate specimen is calculated using the following equation:

$$\sigma_f = \frac{3Pl}{2bd^2} \dots Eq. (7)$$

Where, σ_f = flexural strength of specimen in MPa; P = maximum load in N; l = span length of the specimen in mm, and d = depth of specimen in mm, and b = width of specimen in mm.

Using energy method, the energy absorbed by the specimen during flexural test can be calculated by the area under the flexural load-deflection graph using the following equation:

$$W = \int_0^{\delta} F d\delta \dots Eq. (5)$$

Where; W is the energy absorbed by the specimen (kN.mm); δ is the mid span deflection (mm); F is the flexural load (kN).

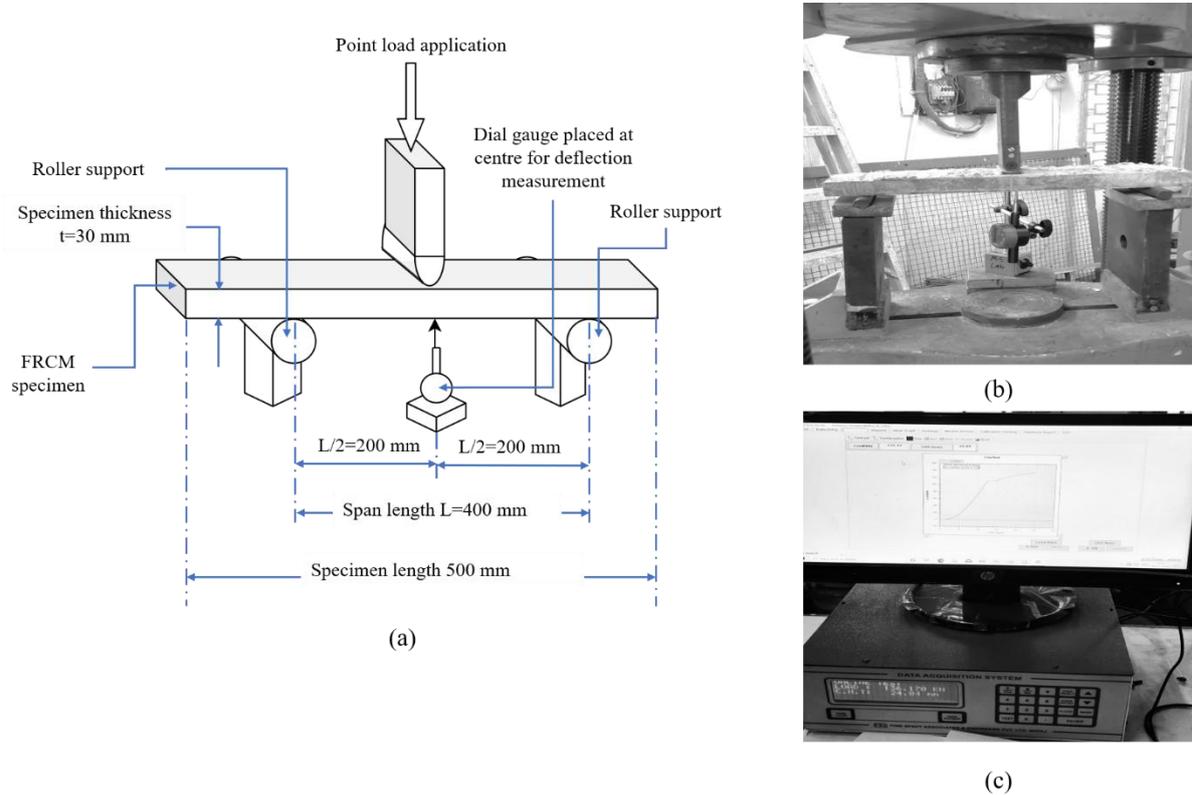


Figure 3.26 Test specimen configuration for flexural test (3-point bending test) for FRCM specimens: (a) schematic representation, (b) front view of experimental set-up with dial gauge, and (c) computer with data acquisition system (UTM equipped with Win software, available in the Department of Applied Mechanics, FTE).