

**INFLUENCE OF YARN CORE-SHEATH STRUCTURE ON
TEXTILE REINFORCED CONCRETE PROPERTIES**

**Executive Summary of the thesis submitted in partial fulfilment of the
requirements for the degree of
DOCTOR OF PHILOSOPHY IN TEXTILE ENGINEERING**

to



THE MAHARAJA SAYAJIRAO UNIVERSITY OF BARODA

by

BARMAN NABOKUMAR CHARGARAM

(FoTE/897)

Under the Guidance of

PROF. SOMESHWAR S. BHATTACHARYA

&

PROF. RAMASAMY ALAGIRUSAMY

**Department of Textile Engineering
Faculty of Technology and Engineering
The Maharaja Sayajirao University of Baroda
Vadodara, Gujarat- 390 001, India**

July 2024

Table of Contents

	Page No.
Thesis Certificate	i
Acknowledgements	ii
Abstract	iv
Table of Contents	vi
List of Tables	xiii
List of Figures	xiv
Abbreviations and Notations	xxvii
Chapter – 1	Introduction and Objectives
1.1	Background and origin of the topic
1.2	Motivation
1.3	Research Objectives
1.4	Organization of the Thesis
Chapter – 2	Literature Review
2.1	Textile Structures
2.2	Textile Reinforced Concrete
2.3	Composition of cementitious matrix for manufacturing TRC
2.4	TRM fabrication methods
2.4.1	Casting
2.4.2	Pre-tensioning (Prestressing)
2.4.3	Hand lay up
2.4.4	Spraying method
2.4.5	Filament Winding
2.4.6	Pultrusion
2.4.7	Combined additive manufacturing of TRC
2.5	Hybrid yarn-based structure
2.5.1	Commingled yarn

	2.5.1.1	Commingled yarn using compressed air jets	25
	2.5.1.2	Online commingling process	27
	2.5.2	Air-jet textured yarn	28
	2.5.3	Powder coated yarn	28
	2.5.4	Cable yarn	29
	2.5.5	DREF spun core-sheath yarn	30
	2.5.6	Braided structure	32
2.6		2-D woven fabric	33
2.7		2-D woven fabric based FRCM	34
	2.7.1	Fibre type	35
	2.7.2	Reinforcement ratio and number of fabric layers	35
	2.7.3	Embedment length	36
	2.7.4	Yarn twisted configuration	36
	2.7.5	Yarn fineness	36
	2.7.6	Yarn geometry and pick density	37
	2.7.8	Fabric grid opening	38
	2.7.9	Weave design	39
	2.7.10	Hybrid fabric	40
2.8		Non-crimp fabrics for TRC reinforcement	41
2.9		Methods of improving fibre-concrete bonding	42
	2.9.1	Surface modification of FRP rods	42
	2.9.2	Modified braided rod structure	42
2.10		Coating textiles	44
	2.10.1	Coating of filament bundle	45
	2.10.2	Mineral-impregnated carbon fibre composites	46
	2.10.3	Plasma treatment	48
	2.10.4	Nano coating	48
	2.10.5	Resin coating of woven fabric	49
2.11		Inclusion of short fibres as secondary reinforcement in TRC	51
2.12		Mechanical Characteristics of FRCM	54
	2.12.1	Strain-Softening and Strain-Hardening response	54

	of FRC Composites	
	2.12.2 Yarn pull-out behaviour in FRCM	56
	2.12.3 Uniaxial tensile behaviour of FRCM	57
	2.12.4 Flexural behaviour of FRCM	58
2.13	Gaps in Literature	58
Chapter – 3	Material and Methods	
3.1	Raw material selection	60
	3.1.1 Fibres	60
	3.1.2 Epoxy resin and hardener	62
	3.1.3 Mortar ingredients	62
3.2	Hybrid yarn development	63
	3.2.1 Core-sheath yarn development	63
	3.2.2 Filament wrapping	65
	3.2.3 Braiding	66
	3.2.4 Thermal treatment	67
3.3	Fabric formation	71
3.4	Fabric composite formation	80
	3.4.1 Compression moulding for thermoplastic fabric composite	80
	3.4.2 Epoxy resin coating for thermoset fabric composite	81
3.5	Yarn sample cross-section examination	81
	3.5.1 Yarn sample preparation	81
3.6	Fabrication of Formwork for casting mortar specimens for pull-out, tensile and flexural test	82
	3.6.1 Formulation of mortar mix proportions	83
	3.6.2 Mortar mixing and casting and curing of concrete specimens	84
	3.6.3 Compaction and curing of FRCM specimens	85
	3.6.4 Slump test	86
	3.6.5 Specimen preparation for yarn pull-out test of yarn reinforced cementitious matrix	87
	3.6.6 Specimen preparation for yarn pull-out test of	87

	FRCM	
	3.6.7 Specimen preparation for uniaxial tensile test of FRCM	87
	FRCM	
	3.6.8 Specimen preparation for flexural test of FRCM	87
3.7	Test method for tensile properties of yarn, fabric and fabric composite	88
3.8	Test method for Compression strength of Cube Specimens	88
3.9	Test method for Split tensile test of Cylinder Specimens	89
3.10	Test method for yarn pull-out behaviour of YRCM and FRCM	90
3.11	Test method for Uniaxial tensile behaviour of FRCM	92
3.12	Test method for Flexural test of FRCM	94
Chapter – 4	Results and Discussion	
4.1	Cross-section micrograph of yarn specimens	96
	4.1.1 Cross-section micrograph of DREF spun core-sheath yarn	96
	4.1.2 Cross-section micrographs of parent, epoxy coated and hybrid yarn	97
4.2	Tensile behaviour of yarn and fabric	100
	4.2.1 Tensile behaviour of parent AR-glass yarn, hybrid yarn and fabric	102
	4.2.2 Tensile behaviour of parent basalt yarn, hybrid yarn and fabric	103
	4.2.3 Effect of mesh opening on tensile behaviour of hybrid yarn based thermoplastic fabric composite	105
	4.2.4 Tensile behaviour of parent carbon yarn, hybrid yarn and fabric	107
	4.2.5 Comparison of tensile behaviour of parent and hybrid AR-glass, basalt, carbon yarns and fabrics	108
	4.2.6 Discussion on tensile behaviour of parent yarn, hybrid yarn and fabric	109
4.3	Cube Compression behaviour	110

4.4	Cylinder split tensile behaviour	111
4.5	Yarn pull-out behaviour of yarn reinforced cementitious mortar	111
4.5.1	Yarn pull-out behaviour of AR-glass YRCM	112
4.5.2	Yarn pull-out behaviour of Basalt YRCM	114
4.5.3	Yarn pull-out behaviour of Carbon YRCM	116
4.5.4	Comparison of yarn pull-out behaviour of different YRCM specimens	118
4.6	Yarn pull-out behaviour of FRCM	119
4.6.1	Yarn pull-out behaviour of AR-glass FRCM	119
4.6.2	Yarn pull-out behaviour of Basalt FRCM	121
4.6.3	Yarn pull-out behaviour from Carbon FRCM	123
4.6.4	Influence of yarn embedment length on pull-out behaviour	125
4.6.5	Comparison of yarn pull-out behaviour from different FRCM specimens	126
4.6.6	Discussion on yarn pull-out behaviour	127
4.7	Uniaxial tensile behaviour of FRCM	128
4.7.1	Uniaxial tensile behaviour of AR-glass FRCM	129
4.7.2	Uniaxial tensile behaviour of Basalt FRCM	131
4.7.3	Comparison of tensile behaviour of parent basalt fabric, hybrid yarn-based basalt TP and TS fabric composite based FRCM specimens	133
4.7.4	Effect of number of layer reinforcement on tensile behaviour of FRCM	135
4.7.5	Effect of mesh size opening of fabric on tensile behaviour of FRCM	137
4.7.6	Uniaxial tensile behaviour of Carbon FRCM	138
4.7.7	Comparison of uniaxial tensile behaviour of different FRCM	140
4.7.8	Crack pattern of FRCM specimens	141
4.8	Flexural behaviour of FRCM	144
4.8.1	Flexural behaviour of AR-glass FRCM	144

4.8.2	Flexural behaviour of Basalt FRCM	146
4.8.3	Comparison of flexural behaviour of parent basalt fabric, hybrid yarn-based basalt TP and TS fabric composite based FRCM specimens	149
4.8.4	Effect of mesh size opening of fabric on flexural behaviour of FRCM	151
4.8.5	Effect of number of layer reinforcement on flexural behaviour of FRCM	152
4.8.6	Flexural behaviour of Carbon FRCM	154
4.8.7	Comparison of flexural behaviour of different FRCM	156
Chapter – 5	Summary and Conclusions	
5.1	Background	158
5.2	Cross-section micrograph of yarn specimens	159
5.3	Tensile behaviour of yarn and fabric	159
5.4	Cylinder split tensile behaviour	159
5.5	Yarn pull-out behaviour of YRCM	160
5.6	Yarn pull-out behaviour of FRCM	160
5.7	Uniaxial tensile behaviour of FRCM	161
5.7.1	Comparison of tensile behaviour of parent, epoxy coated and hybrid yarn-based AR-glass, basalt and carbon FRCM specimens	161
5.7.2	Comparison of tensile behaviour of parent basalt fabric, hybrid yarn-based basalt TP and TS fabric reinforced FRCM specimens	161
5.7.3	Effect of number of layer reinforcement on tensile behaviour of FRCM specimens	162
5.7.4	Effect of mesh size opening of fabric on tensile behaviour of FRCM specimens	163
5.8	Flexural behaviour of FRCM	163
5.8.1	Comparison of flexural behaviour of parent, epoxy coated and hybrid yarn-based AR-glass,	163

	basalt and carbon FRCM specimens	
5.8.2	Comparison of flexural behaviour of parent basalt fabric, hybrid yarn-based basalt TP and TS fabric reinforced FRCM specimens	164
5.8.3	Effect of number of layer reinforcement on flexural behaviour of FRCM specimens	164
5.8.4	Effect of mesh size opening of fabric on flexural behaviour of FRCM specimens	165
5.9	Scope for Future work	166
	List of References	167
	Curriculum Vitae	184
	List of Publications	185

List of Tables

Table No.	Title of Table	Page No.
Table 2.1	Typical fibres used in concrete and their properties	12
Table 2.2	Composition of cementitious matrix used for manufacturing TRC used in various studies	16
Table 3.1	Basic characteristics of the yarns (rovings/tow) used in this study.	61
Table 3.2	Basic properties of the resin and hardener.	62
Table 3.3	Properties of the different binders as mortar constituents.	62
Table 3.4	Process parameters in DREF-3 spinning machine.	64
Table 3.5	Process parameters used in heat treatment operation.	68
Table 3.6	Fabric construction details of various fabrics used in this study.	75 – 79
Table 3.7	Mix proportions of mortar ingredients by weight ratio for FRCM preparation.	83
Table 4.1	Measured perimeter and cross-sectional area of yarn specimens using microscope.	99
Table 4.2	Tensile load and displacement values of uncoated, epoxy coated and hybrid yarns of ARG, basalt, and carbon.	100
Table 4.3	Tensile load and displacement values of uncoated, epoxy coated and hybrid yarn-based fabrics of ARG, basalt, and carbon.	101
Table 4.4	Crack details of failed FRCM specimens after uniaxial tensile test. (n – number of specimens)	142

List of Figures

Figure No.	Title of Figure	Page No.
Figure 2.1	Classification of textiles and textile-based composites for reinforcement in concrete elements.	13
Figure 2.2	The evolution of different types of structural concrete composites.	14
Figure 2.3	A simplified illustration of textile reinforced concrete (TRC).	15
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.	18
Figure 2.5	Pre-stressing techniques: (a) uniaxial prestressing system for producing TRC elements, (b) tensioning frame used in the manufacture of biaxially pre-stressed TRC panels, (c) application of concrete matrix onto pre-stressed aramid TRC panels.	19
Figure 2.6	TRC slab created via hand lay-up method: (a) compaction of concrete layer using roller, (b) placement of fabric layer, and (c) underside view of the laminated.	20
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.	21
Figure 2.8	Schematic of filament winding method used for producing cementitious matrix impregnated laminated composite.	22
Figure 2.9	(a) Schematic representation of a pultrusion setup, (b) actual photograph of the pultrusion process.	23

Figure 2.10	Stepwise schematic representation of combined additive manufacturing of TRC elements.	24
Figure 2.11	Schematic representation of: (a) commingling process for hybrid yarn production, (b) commingling nozzle action, and (c) air texturing nozzle action.	26
Figure 2.12	(a) Yarn pull-out behaviour for various yarn samples, (b) tensile behaviour of TRC specimens reinforced with different yarn samples.	27
Figure 2.13	Schematic diagram of online commingled yarn formation with glass filaments as the reinforcing component and thermoplastic filaments as the matrix.	27
Figure 2.14	Powder coating setup for towpreg production.	29
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.	30
Figure 2.16	DREF III spinning process for producing core-sheath yarn structure.	31
Figure 2.17	Production of micro-braid yarn (MBY) featuring a jute fiber core and a thermoplastic fiber (PP/PLA) sheath using a 16-spindle braiding machine	32
Figure 2.18	Representation of basic 2-D woven structures used for FRCM reinforcement	34
Figure 2.19	Pull-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	37
Figure 2.20	SEM microstructure images depict cement composite reinforced with polyethylene monofilament woven fabrics of varying picks density: a. 5 picks/cm, and b. 10 picks/cm	38
Figure 2.21	Non-crimp fabric (NCFs) for concrete reinforcement with warp	41

	(50K Carbon Roving) and weft (12K Carbon Roving) held together by stitching threads	
Figure 2.22	Different profiling methods used in FRP bars to improve bonding behaviour in concrete	42
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	44
Figure 2.24	Diagram of the yarn impregnation device: (a) full setup, (b) processing in a five-roller foulard, and final shaping	47
Figure 2.25	Images illustrating various surface coatings applied to carbon	49
Figure 2.26	Influence of different surface coatings on the tensile properties of carbon TRC specimens	50
Figure 2.27	Damage comparison of unreinforced and flax fabric reinforced concrete specimens after repeated hammer impact blow	51
Figure 2.28	Cross-linking mechanism in TRC specimens: (a) without the presence of short fibres, and (b) with the incorporation of short fibres	52
Figure 2.29	Influence of SGF and SCF incorporation on the multiple cracking behaviour in TRC plates subjected to tensile loading	52
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)	53
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)	55
Figure 2.32	Illustration depicting a standard load-deformation curve derived from yarn pull-out testing of FRCM	57
Figure 2.33	Tensile stress-strain characteristics of FRCM under uniaxial	57

	loading	
Figure 2.34	Load-deflection characteristics of FRCM under flexural loading	58
Figure 3.1	Different raw materials (fibre, yarn and sliver) used for producing core-sheath hybrid yarn.	60
Figure 3.2	Different constituents used for mortar preparation.	63
Figure 3.3	DREF-3 spinning machine (a) schematic representation, (b) actual machine (FEHRER, Model DREF 3000, used for sample preparation).	64
Figure 3.4	Direct twisting machine for filament wrapping (Model-DirecTwist 2B, Ağteks Ltd., Beylikdüzü, Istanbul, Turkey, used for sample preparation).	65
Figure 3.5	Schematic representation of the hybrid yarn structure: (a) a core high-performance filament strand helically wrapped with a fine polyester yarn, (b) 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.	66
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 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 (Herzog, Model NG 1/16-120, used for sample preparation).	67
Figure 3.7	Thermal treatment set up used for twisted polyester and DREF spun yarn (a) schematic representation and (b) actual machine.	68
Figure 3.8	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.	69
Figure 3.9	Photographs of parent PET yarn and modified PET yarn structures using twisting and braiding process.	69
Figure 3.10	Photographs of parent basalt yarn and basalt-based hybrid yarn	70

	structures without epoxy coating.	
Figure 3.11	Photographs of AR-glass, basalt, and carbon yarn and their hybrid structures coated with epoxy resin.	70
Figure 3.12	Scrim (open mesh) fabric formation using Handloom.	71
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.	72
Figure 3.14	Compression moulding: (a) schematic representation, (b) actual machine (Machine make: SANTEC, used for sample preparation).	80
Figure 3.15	Sample polishing machine (Make: Metatech, Model: Metapol DC-II used for specimen polishing).	81
Figure 3.16	Microscope for examining and capturing yarn cross-sectional images (Mitutoyo-QS-L2010Z/AFC used for obtaining specimen micrographs).	82
Figure 3.17	Fabricated moulds for casting FRCM specimens for investigating: (a) tensile and pull-out behaviour, (b) flexural behaviour.	82
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.	84
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-	85

filled mould with a 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.

- 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. 86
- 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. 87
- 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). 88
- 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). 89
- 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). 91
- 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 93

	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).	
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).	94
Figure 4.1	Cross-sectional micrograph of the BR-PP DREF spun yarn (left) and thermal treated-BR/PP yarn (right) at 6x magnification.	96
Figure 4.2	Microscopic cross-sectional image of parent AR-glass yarn and hybrid AR-glass yarn structures.	97
Figure 4.3	Microscopic cross-sectional image of parent basalt yarn and hybrid basalt yarn structures.	98
Figure 4.4	Microscopic cross-sectional images of parent carbon yarn and hybrid carbon yarn structures.	98
Figure 4.5	AR-glass fabric specimens for tensile test.	102
Figure 4.6	Load displacement plot of (a) AR-glass yarn, epoxy coated AR-glass yarn, and AR-glass hybrid yarn, (b) AR-glass fabric, epoxy coated AR-glass fabric and AR-glass hybrid yarn-based fabrics.	103
Figure 4.7	Basalt fabric specimens for tensile test.	104
Figure 4.8	Load displacement plot of – (a) Basalt yarn, epoxy coated basalt yarn, and basalt hybrid yarn, (b) Basalt fabric, epoxy coated basalt fabric and basalt hybrid yarn-based fabrics.	105
Figure 4.9	Load displacement plot of basalt fabric thermoplastic composites with mesh openings 6 mm x 7 mm and 10 mm x 12 mm.	106
Figure 4.10	Carbon fabric specimens for tensile test.	107
Figure 4.11	Load displacement plot of – (a) Carbon yarn, epoxy coated carbon yarn, and carbon hybrid yarn, (b) Carbon fabric, epoxy	108

	coated carbon fabric and carbon hybrid yarn-based fabrics.	
Figure 4.12	Comparison of load displacement plot of (a) AR-glass, basalt, carbon yarn, and their hybrid yarns, (b) AR-glass, basalt, carbon fabric, and their hybrid yarn-based fabrics.	109
Figure 4.13	Mortar cube specimen after compression test.	110
Figure 4.14	Mortar cylinder specimens after split tensile test – (a) unreinforced mortar, (b) single layer of basalt thermoplastic FRCM.	111
Figure 4.15	(a) Pull-out force and slip behaviour of parent, epoxy-coated, and hybrid AR-glass YRCM specimens, (b) plot representing average bond stress and energy absorbed by AR-glass YRCM specimens during the yarn pull-out test.	112
Figure 4.16	Photographs of different YRCM specimens reinforced with AR-glass yarn, epoxy coated AR-glass yarn, and AR-glass hybrid yarns following yarn pull-out test.	113
Figure 4.17	(a) Pull-out force and slip behaviour of parent, epoxy-coated, and hybrid basalt YRCM specimens, (b) plot representing average bond stress and energy absorbed by basalt YRCM specimens during the yarn pull-out test.	114
Figure 4.18	Photographs of different YRCM specimens reinforced with basalt yarn, epoxy coated basalt yarn, and basalt hybrid yarns subjected to a yarn pull-out test.	116
Figure 4.19	(a) Pull-out force and slip behaviour of parent, epoxy-coated, and hybrid carbon YRCM specimens, (b) plot representing average bond stress and energy absorbed by carbon YRCM during the yarn pull-out test.	117
Figure 4.20	Photographs of different YRCM specimens reinforced with parent carbon yarn, epoxy coated carbon yarn, and carbon hybrid yarns subjected to a yarn pull-out test.	118
Figure 4.21	(a) Pull-out force and slip behaviour of AR-glass, basalt and carbon parent, and hybrid YRCM specimens, (b) plot representing average bond stress and energy absorbed by these specimens during the yarn pull-out test.	118

Figure 4.22	(a) Yarn pull-out force and slip behaviour of parent, epoxy-coated, and hybrid AR-glass FRCM specimens, (b) plot representing average bond stress and energy absorbed by these specimens during the yarn pull-out test.	120
Figure 4.23	Photographs of different FRCM specimens reinforced with AR-glass fabric, epoxy coated AR-glass fabric, and hybrid yarn-based AR-glass fabrics subjected to a yarn pull-out test.	121
Figure 4.24	(a) Yarn pull-out force and slip behaviour of parent, epoxy-coated, and hybrid basalt FRCM specimens, (b) plot representing average bond stress and energy absorbed by these specimens during the yarn pull-out test.	122
Figure 4.25	Photographs of different FRCM specimens reinforced with basalt fabric, epoxy coated basalt fabric, and hybrid yarn-based basalt fabrics subjected to a yarn pull-out test.	123
Figure 4.26	(a) Yarn pull-out force and slip behaviour of parent, epoxy-coated, and hybrid carbon FRCM specimens, (b) plot representing average bond stress and energy absorbed by these specimens during the yarn pull-out test.	124
Figure 4.27	Photographs of different FRCM specimens reinforced with carbon fabric, epoxy coated carbon fabric, and hybrid yarn-based carbon fabrics subjected to a yarn pull-out test.	125
Figure 4.28	(a) Pull-out force and slip behaviour of AR-glass and basalt epoxy-coated FRCM at 25 mm and 50 mm yarn embedment lengths, (b) plot representing average bond stress and energy absorbed by these specimens during the yarn pull-out test.	126
Figure 4.29	(a) Pull-out force and slip behaviour of AR-glass, basalt and carbon parent, and hybrid yarn-based FRCM specimens, (b) plot representing average bond stress and energy absorbed by these specimens during the yarn pull-out test.	127
Figure 4.30	(a) Tensile load versus displacement plot for AR-glass, epoxy coated AR-glass fabric, and AR-glass hybrid yarn-based fabric reinforced FRCM specimens, (b) plot representing average tensile strength and energy absorbed by these FRCM specimens	129

- during the uniaxial tensile test.
- Figure 4.31 Photographs of various failed FRCM specimens reinforced with AR-glass fabric, epoxy-coated AR-glass fabric, and hybrid yarn-based AR-glass fabrics subjected to a uniaxial tensile test. 130
- Figure 4.32 (a) Tensile load versus displacement plot for basalt, epoxy coated basalt fabric, and basalt hybrid yarn-based fabric reinforced FRCM specimens, (b) plot representing average tensile strength and energy absorbed by these FRCM specimens during the uniaxial tensile test. 131
- Figure 4.33 Photographs of various failed FRCM specimens reinforced with basalt fabric, epoxy-coated basalt fabric, and hybrid yarn-based basalt fabrics subjected to a uniaxial tensile test. 133
- Figure 4.34 (a) Tensile load versus displacement plot for parent basalt, epoxy coated thermoset basalt fabric composite, and basalt hybrid yarn-based thermoplastic fabric composite reinforced FRCM specimens, (b) plot representing average tensile strength and energy absorbed by these FRCM specimens during the uniaxial tensile test. 134
- Figure 4.35 Photographs of various failed FRCM specimens reinforced PP-fibers, basalt thermoplastic, and thermoset fabric composites subjected to a uniaxial tensile test. 135
- Figure 4.36 (a) Tensile load versus displacement plot for PP-FRC, ARG-EC-F (1 L), ARG-EC-F (2 L), B-EC-F (1 L), and B-EC-F (2 L) FRCM specimens, (b) plot representing average tensile strength and energy absorbed by these FRCM specimens during the uniaxial tensile test. 136
- Figure 4.37 (a) Tensile load versus displacement plot for basalt hybrid yarn-based thermoplastic fabric composite reinforced FRCM specimens of varying mesh opening sizes (6 mm x 7 mm, and 10 mm x 12 mm), (b) plot representing average tensile strength and energy absorbed by these FRCM specimens during the uniaxial tensile test. 137
- Figure 4.38 (a) Tensile load versus displacement plot for parent carbon, 138

- epoxy coated carbon fabric, and carbon hybrid yarn-based fabric reinforced FRCM specimens, (b) plot representing average tensile strength and energy absorbed by these FRCM specimens during the uniaxial tensile test.
- Figure 4.39 Photographs of various failed FRCM specimens reinforced with carbon fabric, epoxy-coated carbon fabric, and hybrid yarn-based carbon fabrics subjected to a uniaxial tensile test. 139
- Figure 4.40 (a) Tensile load versus displacement plot for AR-glass, basalt and carbon parent, and hybrid FRCM specimens, (b) plot representing average tensile strength and energy absorbed by these FRCM specimens during the uniaxial tensile test. 140
- Figure 4.41 Plot showing number of cracks and crack spacing in various FRCM specimens: (a) AR-glass, (b) basalt, (c) carbon; (d) PP-FRC and number of layers comparison; (e) parent basalt, thermoplastic and thermoset fabric composite. 143
- Figure 4.42 (a) Flexural load versus mid-span deflection plot for parent AR-glass fabric, epoxy coated AR-glass fabric, and AR-glass hybrid yarn-based fabric reinforced FRCM specimens, (b) plot representing average flexural strength and energy absorbed by these FRCM specimens during the flexural test. 145
- Figure 4.43 Photographs of various failed FRCM specimens reinforced with AR-glass fabric, epoxy-coated AR-glass fabric, and hybrid yarn-based AR-glass fabrics subjected to a flexural test. 146
- Figure 4.44 (a) Flexural load versus mid-span deflection plot for parent basalt fabric, epoxy coated basalt fabric, and basalt hybrid yarn-based fabric reinforced FRCM specimens, (b) plot representing average flexural strength and energy absorbed by these FRCM specimens during the flexural test. 147
- Figure 4.45 Photographs of various failed FRCM specimens reinforced with basalt fabric, epoxy-coated basalt fabric, and hybrid yarn-based basalt fabrics subjected to a flexural test. 148
- Figure 4.46 (a) Flexural load versus mid-span deflection plot for parent basalt, epoxy coated thermoset basalt fabric composite, and

- basalt hybrid yarn-based thermoplastic fabric composite reinforced FRCM specimens, (b) plot representing average flexural strength and energy absorbed by these FRCM specimens during the flexural test.
- Figure 4.47 Photographs of failed basalt epoxy coated FRCM and basalt thermoplastic fabric composite-based FRCM after flexural test. 150
- Figure 4.48 (a) Flexural load versus mid-span deflection plot for basalt hybrid yarn-based thermoplastic fabric composite reinforced FRCM specimens of varying mesh opening sizes (6 mm x 7 mm, and 10 mm x 12 mm), (b) plot representing average flexural strength and energy absorbed by these FRCM specimens during the flexural test. 151
- Figure 4.49 (a) Flexural load versus mid-span deflection plot for unreinforced plain mortar, PP-FRC, and FRCM specimens reinforced with B-PP-1_PET_TP-F (2 L), B-PP-1_PET_TP-F (4 L), and B-PP-1_PET_TP-F (6 L), (b) plot representing average flexural strength and energy absorbed by these FRCM specimens during the flexural test. 152
- Figure 4.50 Photographs of failed unreinforced concrete and PP-FRC specimens after flexural test. 154
- Figure 4.51 (a) Flexural load versus mid-span deflection plot for parent carbon fabric, epoxy coated carbon fabric, and carbon hybrid yarn-based fabric reinforced FRCM specimens, (b) plot representing average flexural strength and energy absorbed by these FRCM specimens during the flexural test. 155
- Figure 4.52 Photographs of various failed FRCM specimens reinforced with carbon fabric, epoxy-coated carbon fabric, and hybrid yarn-based carbon fabrics subjected to a flexural test. 156
- Figure 4.53 (a) Flexural load versus mid-span deflection plot for AR-glass, basalt and carbon parent, and hybrid FRCM specimens, (b) plot representing average flexural strength and energy absorbed by these FRCM specimens during the flexural test. 157

Table of Contents for the Executive Summary of the Ph.D. Thesis

	Page No.
1. Research Motivation	23
2. Research Objectives	24

3. Research Methodology	25
4. Key Findings	31
5. Conclusions	33
6. Recommendations for Future work	35
7. List of Publications	36
8. References	37

1. Research Motivation

High performance fibres such as Carbon, alkali resistant glass (AR glass), basalt have found large interest in composite industry. These fibres have superior mechanical properties and are non-corrosive in nature making them suitable for building infrastructure applications in form of fibre reinforced plastics (FRPs) and textile reinforced concrete (TRC). The hybrid yarn

structure can help to combine the superior tensile properties of high-performance fibres and ductile behaviour of polypropylene and polyester fibres and has the potential to enhance the properties of cement composites and improve yarn-matrix bonding. Previous research confirms the greater advantages of hybrid yarn and fabric structure in concrete in terms of cost and mechanical properties however limited research was done in this area [28]–[32], [34], [35]. The yarn structural modification such as twist, crimped geometry also has positive effect on the pull-out (fibre-concrete bond) behaviour of TRC.

High-performance yarn bundles, such as carbon, comprising thousands of fine filaments, are prone to abrasion and filament breakage during the weaving process. A solution to this challenge involves adopting a core-sheath structure, where a sheath made of polypropylene fibre is applied over the core of the high-performance filament bundle using the DREF-3 spinning process. The resulting core-sheath structure undergoes a short heat-setting process to preserve the integrity of the sheath fibres during weaving. This ensures that the sheath remains intact while maintaining adequate flexibility for the weaving process. This approach has proven effective in reducing filament breakage during weaving operations. Furthermore, the DREF spinning process ensures a very high rate of production with minimal or no damage to the core yarn. Importantly, this method enables the production of hybrid yarns with a diverse range of core-to-sheath ratios without introducing twist to the core bundle [36], [37].

Cable yarn is created by uniformly and spirally wrapping a surface filament strand (surface yarn) over a core filament strand (core yarn) without twisting the individual strands [38]. This principle is also applied in hollow spindle spinning, wrap spinning, and co-wrapping techniques. The core filament offers load-bearing strength, while the surface filament serves to protect the core from abrasion and provides a ribbed surface texture for mechanical anchorage in TRC [20].

Taking into account the aforementioned aspects, the current research aimed to investigate the impact of the hybrid (core-sheath) yarn structure on the mechanical properties of TRC.

2. Research Objectives

The present study aims at developing a hybrid yarn structure that can be incorporated in woven fabric structure which have good mechanical interlocking (anchorage) effect with

cementitious matrix (mortar). To fulfil this objective core-sheath hybrid yarns have been produced using DREF-3 spinning method and helical wrapping was done using direct twisting and braiding machine to incorporate helical configuration of polyester (PET) yarn in the core yarn strand. The hybrid yarn structure is woven into woven scrim fabric (mesh fabric) and coated with epoxy resin. The fabric is reinforced into concrete specimen to investigate pull-out, tensile and flexural properties.

The following are the sub-objectives for the present work:

- (i) To develop core-sheath yarn structures using Basalt, Carbon and AR-glass roving (as core components) and polypropylene fibre (as sheath fibres) using DREF-3 spinning method.
- (ii) To incorporate helical configuration in yarn structure: (a) Twisting of PET filaments through Direct twisting machine, (b) helical wrapping of twisted PET filaments on core-sheath yarn structure through braiding machine.
- (iii) To compare the tensile behaviour of parent and hybrid yarn structures and their corresponding plain-woven fabrics.
- (iv) To investigate the influence of parent and hybrid yarn structures on the yarn pull-out behaviour of fabric-reinforced concrete.
- (v) To compare the pull-out behaviour of fabric-reinforced concrete and evaluate the effectiveness of yarn structure used for helical wrapping, formed through (a) direct twisting, and (b) braiding machine.
- (vi) To compare the tensile, and flexural characteristics of concrete reinforced with woven fabric made from hybrid yarn structures and parent yarn structures.
- (vii) To examine the influence of combined reinforcements, comprising of discrete polypropylene fibres and a woven fabric structure (TRC), and compare them with plain (unreinforced) concrete, and polypropylene fibre-reinforced concrete (FRC), in terms of their mechanical properties.

3. Research Methodology

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 fibres are used.

3.1 Development of core-sheath yarn structure

DREF-3 spinning technique was employed for the development of core-sheath (hybrid yarn) structure. The core comprises high-performance basalt, AR-glass, and carbon, while the sheath consists of polypropylene staple fibres. Thermal heat setting is then employed to enhance the weavability and structural integrity of the hybrid yarn.

3.2 Development of Cable yarn

Subsequently, cable yarn consists of high-performance filament core (basalt, AR-glass, and carbon) helically wrapped configuration using a PET yarn (twisted and braided PET filaments) is developed by utilising a single carrier in a braiding machine.

3.3 Plain woven scrim fabric formation

The cable yarn is woven into a plain weave scrim fabric using a handloom, with flexible inserts maintaining the distance between subsequent picks, later removed after weaving. The scrim fabric facilitates the flow of cementitious mortar, and the grid size is selected considering the particle size of the fine aggregate.

3.4 Fabric composite formation

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 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.

3.5 Epoxy resin coating

Following this, epoxy resin coating is applied using hand lay-up method to improve the fabric's structural stability and prevent distortion during handling. The resin treatment binds the multifilament in the core yarn strand, creating a monofilament-type effect and enhancing load-bearing ability.

3.6 Mortar formulation

Fine-grained mortar is recommended for FRCM specimens to facilitate ease of mortar flow in between the fabric interstices. 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. Additionally, the addition of polypropylene fibres in limited quantities has been found to prevent plastic shrinkage and improve tensile properties. Initially, a review of experimental studies from the literature was conducted, followed by mix proportion trials, including slump tests, to evaluate mortar workability before finalizing the mix proportions for this study. The mortar was mixed using a motor-operated rotary drum mixer.

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. 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.

3.7 Fabrication of TRC elements

The process continues with the fabrication of Textile-Reinforced Concrete (TRC) elements (plate specimens) using the casting method in fabricated formworks.

3.7.1 *Specimen preparation for yarn pull-out test of yarn reinforced cementitious matrix*

For the yarn pull-out test, 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.

3.7.2 *Specimen preparation for yarn pull-out test of FRCM*

For the yarn pull-out test from fabric-reinforced mortar, 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.

3.7.3 Specimen preparation for uniaxial tensile test of FRCM

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.

3.7.4 Specimen preparation for flexural test of FRCM

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

3.7.5 Compaction and curing of FRCM specimens

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. 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. After 27 days, the mortar specimens are removed from the water bath, and various tests (pull-out, tensile, and flexural) are performed.

3.8 Test method for tensile properties of yarn, fabric and fabric composite

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. 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). Five samples were tested for each specimen. For fabric composite specimens, the specimen width was maintained at 40 mm.

3.9 Test method for compression strength of 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. 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.

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

$$\sigma_c = \frac{P}{A_c} \dots Eq. (1)$$

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

3.10 Test method for Split tensile test of 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.

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

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

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

3.11 Test method for yarn pull-out behaviour of YRCM and FRCM

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. [147]–[149]. 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 (15 mm x 60 mm x 500 mm) 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.

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.

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

$$\text{Average Bond stress } (\tau_b) = \frac{\text{Pull out force } (F_r)}{\text{Nominal contact surface } (U_r \times l_e)} \dots \text{Eq. (3)}$$

Where, U_r represents the contact perimeter of the roving (yarn) as measured by a microscope, and l_e

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 expression:

$$W = \int_0^{\delta} F d\delta \dots \text{Eq. (4)}$$

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

3.12 Test method for Uniaxial tensile behaviour of FRCM

The uniaxial tensile test of the plate specimen (15 mm x 60 mm x 500 mm) 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. LVDTs are attached to both sides of the tensile specimen to measure displacement and are connected to an LVDT signal conditioner and data logger. Tensile load and deflection are recorded and plotted accordingly.

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

$$\sigma_t = \frac{P}{A_c} \dots \text{Eq. (5)}$$

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 mm².

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 expression:

$$W = \int_0^{\delta} F d\delta \dots Eq. (4)$$

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

3.13 Test method for Flexural test of FRCM

The three-point bending test was conducted on both unreinforced and reinforced (FRCM) specimens using a 100 kN capacity with load cell of 50kN on a universal testing machine (UTM) equipped with a 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.

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

$$\sigma_f = \frac{3Pl}{2bd^2} \dots Eq. (6)$$

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 expression:

$$W = \int_0^{\delta} F d\delta \dots Eq. (4)$$

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

4. Key Findings

1. The tensile test reveals that among AR-glass, basalt, and carbon yarns of similar linear density, carbon exhibits the highest peak load, followed by basalt, with AR-glass having the lowest. This trend is consistent in both hybrid yarns and fabric specimens, reflecting their inherent mechanical properties.
2. Reinforcing a mortar cylinder specimen with a single layer of Basalt-PP-PET thermoplastic fabric composite increased the split tensile strength by 12%.
3. The yarn pull-out test for uncoated AR-glass, basalt, and carbon yarn reinforced cementitious mortar (YRCM) specimens, as well as their hybrid structures, shows carbon achieving the highest pull-out load, followed by basalt and AR-glass. All hybrid YRCM specimens surpass their parent counterparts in peak pull-out load, highlighting improved pull-out behaviour through yarn hybridization.
4. The yarn pull-out test for uncoated AR-glass, basalt, and carbon fabric reinforced cementitious mortar (FRCM) specimens, as well as their hybrid counterparts, reveals that carbon achieves the highest pull-out load, followed by basalt, with AR-glass showing the lowest. Hybrid and uncoated carbon yarns outperform their AR-glass and basalt counterparts in peak pull-out load, bond stress, and energy absorption. Carbon FRCM specimens exhibit more fibre pull-out incidents due to the fine filaments in the carbon yarn bundle and the superior tensile properties of carbon filaments.
5. The uniaxial tensile test results reveal that carbon FRCM specimens achieve the highest tensile strength and energy absorption, followed by basalt and AR-glass. Hybrid yarn-based FRCM specimens outperform their uncoated counterparts in both tensile strength and energy absorption, regardless of fibre type, aligning with the trends observed in fabric tensile tests. Replacing uncoated fabric with epoxy-coated or hybrid yarn-based fabric increases the average number of cracks and reduces crack spacing in failed FRCM specimens.
6. Comparing the tensile load-displacement behaviour of different basalt yarn-based FRCM specimens—parent (uncoated), epoxy-coated thermoset (TS) fabric composite, and hybrid yarn-based thermoplastic (TP) fabric composite—the epoxy-coated TS composite exhibited the highest tensile load, followed by the hybrid yarn TP composite, with the uncoated basalt having the lowest. Reinforcing basalt with TP fabrics increases tensile load and strength by 11.29%, while TS fabrics improve these properties by 21.86%. Energy absorption increases by 31.46% with the hybrid yarn thermoplastic composite and 47.44% with the epoxy-coated thermoset composite.

7. Comparing the tensile behaviour of PP fibre-reinforced mortar (PP-FRC, control) with AR-glass and basalt epoxy-coated TS FRCM specimens reveals significant improvements. With one fabric layer, AR-glass and basalt FRCM specimens showed tensile peak load increases of 250% and 433%, respectively, while two layers achieved increases of 740% and 1092%. Energy absorption improved by 470% and 1485% with one layer and by 2292% and 7234% with two layers, respectively.
8. The tensile load-displacement behaviour of basalt hybrid yarn-based TP FRCM specimens shows a 20% increase in tensile peak load, and a 43.25% improvement in energy absorption as the mesh size decreases from 10 mm × 12 mm to 6 mm × 7 mm. This improvement is due to the higher number of warp and weft yarns in the smaller mesh size, with six load-bearing warp yarns in the 6 mm × 7 mm mesh compared to four in the 10 mm × 12 mm mesh, while maintaining the same specimen dimensions.
9. Flexural tests reveal that carbon FRCM specimens exhibit the highest flexural peak load, strength, and energy absorption, followed by basalt and AR-glass. Hybrid yarn-based FRCM specimens outperform their uncoated counterparts across all fibre types. This performance is consistent with the tensile properties observed in fabric tensile tests and the uniaxial tensile tests of FRCM specimens.
10. Reinforcing FRCM specimens with TS and TP basalt fabrics increases flexural load by 38% and 48%, respectively, and energy absorption by 172% and 561%.
11. The flexural behaviour of plain mortar (PC), PP fibre-reinforced mortar (PP-FRC), and basalt TP fabric-reinforced FRCM specimens shows significant improvements with reinforcement. Replacing PC with PP-FRC increases flexural load and strength by 123%, while adding fabric layers enhances these by 297% (2 layers), 490% (4 layers), and 693% (6 layers). Energy absorption increases by 222% with PP-FRC and by 2986%, 5980%, and 15380% for 2, 4, and 6 fabric layers, respectively.
12. The flexural behaviour of basalt hybrid yarn-based TP FRCM specimens shows a 31% improvement in flexural peak load and strength, and a 72% increase in energy absorption as the mesh size decreases from 10 mm × 12 mm to 6 mm × 7 mm. This is due to the higher number of warp and weft yarns in the smaller mesh, with 10 yarn strands in the 6 mm × 7 mm fabric compared to 6 in the 10 mm × 12 mm fabric.

5. Conclusions

1. Parent roving bundles with smooth multi-filaments have poor cohesion, causing them to spread in the matrix and form flattened cross-sections. Epoxy-coated bundles resist spreading, resulting in oval or elliptical shapes. Hybrid yarns, secured by PP sheaths and PET filaments, form oval or circular cross-sections. These configurations influence the interfacial bonding and bond stress between the filaments and the mortar matrix.
2. Yarn hybridization and epoxy coating enhance the tensile behaviour of AR-glass, basalt, and carbon yarns. In DREF spun yarn, the PP sheath binds the multifilament core, reinforced by PET wraps, while epoxy stiffens the yarn, enabling monofilament-like performance. This improves load-bearing capacity, load-transfer efficiency, tensile strength, and ductility.
3. The pull-out behaviour of YRCM specimens suggests that helically wrapped PET yarns (twisted and braided yarn) enhance surface roughness, improving anchorage with the mortar matrix. Epoxy coating and PP sheath fibers further secure the core high-performance filaments within the PET-wrapped yarn.
4. FRCM specimens show superior pull-out behaviour to YRCM specimens, aided by surface roughness from helically wrapped PET yarns (twisted and braided), epoxy coating, and the assistance offered by the weft yarn of the woven fabric structure enhancing yarn-mortar bonding. In contrast, YRCM pull-out load relies primarily on surface roughness from PET wraps and epoxy coating.
5. Unlike basalt and carbon hybrid yarns, the AR-glass hybrid yarn exhibited telescopic failure under pull-out loading, likely due to poor epoxy resin impregnation through the PP sheath, which resulted in inadequate wetting of the AR-glass filaments. During the pull-out test, the inner core filaments slipped, leaving the sleeve in the mortar, with no significant cracks, damage, or spalling observed in the mortar specimen.
6. In the uniaxial tensile test, replacing the parent (uncoated) fabric with epoxy-coated or hybrid yarn-based fabric increases the number of cracks and reduces crack spacing in failed FRCM specimens, regardless of fibre type. This indicates more uniform load transfer to the mortar. Fine cracks and multiple cracking under tensile load are beneficial, especially in hybrid yarn-based specimens.
7. Comparing the tensile load-displacement behaviour of different basalt yarn-based FRCM specimens—parent (uncoated), epoxy-coated TS fabric composite, and hybrid yarn-based TP fabric composite—shows that resin coating and impregnation improve load-bearing and load-sharing, allowing the fabric to sustain higher tensile loads.

Post-test images reveal that replacing the parent basalt fabric with epoxy-coated TS or hybrid yarn-based TP composites increases the number of cracks and reduces crack spacing in FRCM reinforcement.

8. Comparing the tensile behaviour of PP fibre-reinforced mortar (PP-FRC, control) with AR-glass and basalt epoxy-coated FRCM specimens shows that fabric reinforcement significantly improves tensile properties. High-performance fibres, combined with PP fibres as secondary reinforcement, enhance load-bearing capacity, energy absorption, and ductility. Failed specimen images reveal that the PP-FRC specimen exhibited two cracks, leading to complete failure, while AR-glass and basalt FRCM specimens failed through fibre fracture and pull-out, with multiple fine cracks. Increasing fabric layers from one to two reduces crack spacing and increases the number of cracks, regardless of fibre type.
9. The tensile load-displacement behaviour of basalt hybrid yarn-based thermoplastic FRCM specimens with grid openings of 6 mm x 7 mm and 10 mm x 12 mm show failure through fibre fracture and pull-out, with multiple fine cracks along the specimen width. Images reveal a slight increase in crack number and decrease in crack spacing as the fabric mesh opening size reduces from 10 mm x 12 mm to 6 mm x 7 mm.
10. Post-failure analysis of FRCM specimens subjected to flexural testing reveals enhanced crack distribution and an increase in microcracks in epoxy-coated TS and hybrid yarn-based TP specimens. In TP-based FRCM specimens, hybrid yarns fail through a combination of fibre fracture and pull-out, with warp yarns bridging to prevent the full separation of the FRCM plate.
11. Thermoplastics (TP) offer superior energy absorption, while resin coating enhances load-bearing capacity, enabling higher flexural loads and deflection. Parent basalt fabric fails entirely through fibre fracture, while hybrid TP composites fail via fibre fracture and pull-out, with fabric bridging preventing full separation. TS composites resist complete rupture, maintaining strong mortar bonding. Images show finer microcracks, improved crack distribution, and reduced spacing with epoxy-coated TS and hybrid yarn-based TP fabrics.
12. Under flexural loading, unreinforced PC and PP-FRC specimens exhibited failure through single major cracks, whereas FRCM specimens (reinforced with basalt TP fabric composite) demonstrated fibre rupture, pull-out, and the formation of multiple

fine cracks. Increasing the number of fabric layers improved crack distribution and reduced crack spacing. Specimens with 4 and 6 fabric layers displayed fabric bridging, which prevented complete separation and significantly enhanced performance.

13. The influence of mesh opening sizes (10 mm × 12 mm and 6 mm × 7 mm) on the flexural behaviour of basalt hybrid yarn-based TP fabric composite-reinforced FRCM specimens indicates that, regardless of mesh size, the failed specimens exhibited fibre fracture, pull-out, fabric bridging, and fine microcracks along the width, effectively preventing complete separation.

6. Recommendations for Future work

- This study focused on comparing the mechanical performance of hybrid and non-hybrid yarn-based FRCM specimens. Future research could explore the durability, thermal performance, and fire resistance of these materials.
- In this study, DREF spinning, braiding, and cabling methods were used to produce hybrid yarn. Investigating other hybrid yarn manufacturing methods and their suitability for FRCM specimens would be valuable.
- Further research could investigate the mechanical performance of FRCM specimens using other thermoplastic fibres such as PLA, PE, and Nylon in hybrid yarn structures.
- Additionally, developing and analysing numerical models based on hybrid and non-hybrid yarn-based FRCM could provide deeper insights into their performance.

7. List of Publications

Journal Publication

1. Nabo Kumar Barman, S. S. Bhattacharya, and R. Alagirusamy(2024). Textile structures in concrete reinforcement. *Textile Progress*, 56(1), 1–229. <https://doi.org/10.1080/00405167.2023.2266930>

Book Chapter

1. Nabo Kumar Barman, Alagirusamy Ramasamy, Someshwar S. Bhattacharya. “Improving performance of concrete structures with textile reinforcements” In *Emerging Trends in Traditional and Technical Textiles-Select Proceedings of ICETT 2023*, edited by Vinay Midha, Raul Fanguero, S. Rajendran, First Edition, Springer Proceedings in Materials (SPM, volume 55)Springer Singapore, August 2024, eBook ISBN 978-981-97-5902-6 (accepted for publication, in press)
2. Nabo Kumar Barman, R. Alagirusamy, and S. S. Bhattacharya. “Flexible Towpregs and Thermoplastic Composites for Civil Engineering Applications.” In *Flexible Towpregs and Their Thermoplastic Composites*, edited by Ramasamy Alagirusamy, First Edition, 357–96. Boca Raton: CRC Press, 2022. <https://doi.org/10.1201/9781003049715-13>.
3. Nabo Kumar Barman, S. S. Bhattacharya, R. Alagirusamy. “Development of Hybrid Yarn Based Woven Textile Structures for Textile Reinforced Concrete Applications” In *Industrial Textiles – Products, Applications and Prospects*, edited by G. Thilagavathi, S. Periyasamy, J. Krishnasamy, Satyajeet B. Chaudhari, First Edition, Woodhead Publishing India Pvt. Ltd., New Delhi, India, 2021,e-ISBN: 978-81-954048-9-6

Conference presentations

1. Nabo Kumar Barman, S. S. Bhattacharya, and R. Alagirusamy. “Development of Hybrid Yarn Based Woven Textile Structures for Textile Reinforced Concrete Applications” In *Fifth International Conference on Industrial Textiles – Products, Applications and Prospects*, PSG College of Technology, Coimbatore, Tamilnadu, India, 23rd August 2020.
2. Nabo Kumar Barman, S. S. Bhattacharya, and R. Alagirusamy. “Application of Textile Structures and Composites to improve performance and durability of Building Structures”. In *2nd ICETT International Conference on Emerging Trends in Traditional and Technical Textiles*, Department of Textile Technology, Dr. B. R. Ambedkar National Institute of Technology, Jalandhar, Punjab, India. 1stNovember 2019.

8. List of References

- [1] B. Huang *et al.*, “A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials,” *One Earth*, vol. 3, no. 5, pp. 564–573, Nov. 2020, doi: 10.1016/j.oneear.2020.10.010.
- [2] E. Yilmaz, H. Arslan, and A. Bideci, “Environmental performance analysis of insulated composite facade panels using life cycle assessment (LCA),” *Constr. Build. Mater.*, vol. 202, pp. 806–813, Mar. 2019, doi: 10.1016/j.conbuildmat.2019.01.057.
- [3] D. J. M. Flower and J. G. Sanjayan, “Green house gas emissions due to concrete manufacture,” *Int. J. Life Cycle Assess.*, vol. 12, no. 5, pp. 282–288, Jul. 2007, doi: 10.1007/s11367-007-0327-3.
- [4] N. W. Portal, K. Lundgren, H. Wallbaum, and K. Malaga, “Sustainable potential of textile-reinforced concrete,” *J. Mater. Civ. Eng.*, vol. 27, no. 7, 2015, doi: 10.1061/(ASCE)MT.1943-5533.0001160.
- [5] A. E. Naaman, “Textile Reinforced Cement Composites: Competitive status and research directions,” in *International RILEM Conference on Material Science*, 2010, pp. 3–22, [Online]. Available: <https://www.rilem.net/images/publis/pro075-001.pdf>.
- [6] F. de A. Silva, B. Mobasher, and R. D. T. Filho, “Cracking mechanisms in durable sisal fibre reinforced cement composites,” *Cem. Concr. Compos.*, vol. 31, no. 10, pp. 721–730, Nov. 2009, doi: 10.1016/j.cemconcomp.2009.07.004.
- [7] P. Baruah and S. Talukdar, “A comparative study of compressive, flexural, tensile and shear strength of concrete with fibres of different origins,” *Indian Concr. J.*, vol. 81, no. 7, pp. 17–24, Jul. 2007.
- [8] E. Awwad, M. Mabsout, B. Hamad, M. T. Farran, and H. Khatib, “Studies on fibre-reinforced concrete using industrial hemp fibres,” *Constr. Build. Mater.*, vol. 35, pp. 710–717, Oct. 2012, doi: 10.1016/j.conbuildmat.2012.04.119.
- [9] A. Bentur and S. Mindess, *Fibre Reinforced Cementitious Composites*. CRC Press, 2006.

- [10] M. Ali, A. Liu, H. Sou, and N. Chouw, “Mechanical and dynamic properties of coconut fibre reinforced concrete,” *Constr. Build. Mater.*, vol. 30, pp. 814–825, May 2012, doi: 10.1016/j.conbuildmat.2011.12.068.
- [11] A. Peled, B. Mobasher, and A. Bentur, *Textile Reinforced Concrete*. CRC Press, 2017.
- [12] A. Peled, A. Bentur, and D. Yankelevsky, “Woven fabric reinforcement of cement matrix,” *Adv. Cem. Based Mater.*, vol. 1, no. 5, pp. 216–223, Jul. 1994, doi: 10.1016/1065-7355(94)90027-2.
- [13] T. Quadflieg, O. Stolyarov, and T. Gries, “Influence of the fabric construction parameters and roving type on the tensile property retention of high-performance rovings in warp-knitted reinforced fabrics and cement-based composites,” *J. Ind. Text.*, vol. 47, no. 4, pp. 453–471, Nov. 2017, doi: 10.1177/1528083716652831.
- [14] A. Peled, A. Bentur, and D. Yankelevsky, “Effects of Woven Fabric Geometry on the Bonding Performance of Cementitious Composites,” *Adv. Cem. Based Mater.*, vol. 7, no. 1, pp. 20–27, Jan. 1998, doi: 10.1016/S1065-7355(97)00012-6.
- [15] A. Peled, Z. Cohen, Y. Pasder, A. Roye, and T. Gries, “Influences of textile characteristics on the tensile properties of warp knitted cement based composites,” *Cem. Concr. Compos.*, vol. 30, no. 3, pp. 174–183, Mar. 2008, doi: 10.1016/j.cemconcomp.2007.09.001.
- [16] B. Mobasher, N. Jain, C. M. Aldea, and C. Soranakom, “Mechanical Properties of Alkali Resistant Glass Fabric Composites for Retrofitting Unreinforced Masonry Walls,” in *SP-244: Thin Fibre and Textile Reinforced Cementitious Systems*, 2007, vol. SP-244, pp. 125–140, doi: 10.14359/18756.
- [17] M. Popescu, M. Rippmann, T. Van Mele, and P. Block, “Complex concrete casting : Knitting stay-in-place fabric formwork,” in *Proceedings of the IASS Annual Symposium 2016 : Spatial Structures in the 21st Century*, 2016, pp. 1–9, [Online]. Available: https://block.arch.ethz.ch/brg/files/POPESCU_2016_IASS_complex-concrete-casting-knitting-stay-in-place-formwork_1545049665.pdf.
- [18] L. N. Koutas, Z. Tetta, D. A. Bournas, and T. C. Triantafillou, “Strengthening of Concrete Structures with Textile Reinforced Mortars: State-of-the-Art Review,” *J. Compos. Constr.*, vol. 23, no. 1, pp. 1–20, Feb. 2019, doi: 10.1061/(ASCE)CC.1943-

5614.0000882.

- [19] J. Hegger and S. Voss, “Investigations on the bearing behaviour and application potential of textile reinforced concrete,” *Eng. Struct.*, vol. 30, no. 7, pp. 2050–2056, Jul. 2008, doi: 10.1016/j.engstruct.2008.01.006.
- [20] T. Gries, M. Raina, T. Quadflieg, and O. Stolyarov, “Manufacturing of textiles for civil engineering applications,” in *Textile Fibre Composites in Civil Engineering*, T. Triantafillou, Ed. Elsevier, 2016, pp. 3–24.
- [21] T. Triantafillou, “Strengthening of existing concrete structures: Concepts and structural behavior,” in *Textile Fibre Composites in Civil Engineering*, T. Triantafillou, Ed. Elsevier, 2016, pp. 303–322.
- [22] N. K. Barman, S. S. Bhattacharya, and R. Alagirusamy, “Textile structures in concrete reinforcement,” *Text. Prog.*, vol. 56, no. 1, pp. 1–229, Jan. 2024, doi: 10.1080/00405167.2023.2266930.
- [23] N. K. Barman, S. S. Bhattacharya, and R. Alagirusamy, “Development of Hybrid Yarn based Woven Textile Structures for Textile Reinforced Concrete Applications,” in *Fifth International Conference on Industrial Textiles – Products, Applications and Prospects*, 2020.
- [24] A. Peled and A. Bentur, “Fabric structure and its reinforcing efficiency in textile reinforced cement composites,” *Compos. Part A Appl. Sci. Manuf.*, vol. 34, no. 2, pp. 107–118, Feb. 2003, doi: 10.1016/S1359-835X(03)00003-4.
- [25] A. Peled and A. Bentur, “Geometrical characteristics and efficiency of textile fabrics for reinforcing cement composites,” *Cem. Concr. Res.*, vol. 30, no. 5, pp. 781–790, May 2000, doi: 10.1016/S0008-8846(00)00239-8.
- [26] O. Weichold and M. Hojczyk, “Size Effects in Multifilament Glass-Rovings: The Influence of Geometrical Factors on Their Performance in Textile-Reinforced Concrete,” *Text. Res. J.*, vol. 79, no. 16, pp. 1438–1445, 2009, doi: 10.1177/0040517508100628.
- [27] P. Kravaev *et al.*, “Commingling Yarns for Reinforcement of Concrete,” *4th Colloq. Text. Reinf. Struct.*, pp. 1–13, 2009, [Online]. Available:

http://www.qucosa.de/fileadmin/data/qucosa/documents/436/paper02_aa11_qucosa.pdf.

- [28] S. Janetzko, P. Kravaev, T. Gries, W. Brameshuber, M. Schneider, and J. Hegger, “TEXTILE REINFORCEMENTS WITH SPREAD AND COMMINGLED YARN STRUCTURES,” in *International RILEM Conference on Material Science – MATSCI, Aachen 2010*, 2010, vol. I, pp. 37–44.
- [29] H. Jamshaid, R. Mishra, J. Militký, and M. T. Noman, “Interfacial performance and durability of textile reinforced concrete,” *J. Text. Inst.*, vol. 109, no. 7, pp. 879–890, Jul. 2018, doi: 10.1080/00405000.2017.1381394.
- [30] M. Varsei, S. Shaikhzadeh Najar, M. Hosseini, and M. Seyed Razzaghi, “Bending properties of fine-grained concrete composite beams reinforced with single-layer carbon/polypropylene woven fabrics with different weave designs and thread densities,” *J. Text. Inst.*, vol. 104, no. 11, pp. 1213–1220, Nov. 2013, doi: 10.1080/00405000.2013.787269.
- [31] S. Gopinath, A. Prakash, and A. K. F. Ahmed, “Synergy of hybrid textile reinforced concrete under impact loading,” *Sādhanā*, vol. 45, no. 1, p. 72, Dec. 2020, doi: 10.1007/s12046-020-1312-9.
- [32] M. Kurban, O. Babaarslan, and İ. H. Çağatay, “Hybrid Yarn Composites for Construction,” in *Textiles for Advanced Applications*, no. 2016, InTech, 2017, pp. 135–160.
- [33] M. Kurban, O. Babaarslan, and İ. H. Çağatay, “Investigation of the flexural behavior of textile reinforced concrete with braiding yarn structure,” *Constr. Build. Mater.*, vol. 334, no. November 2021, p. 127434, Jun. 2022, doi: 10.1016/j.conbuildmat.2022.127434.
- [34] A. Peled, B. Mobasher, and Z. Cohen, “Mechanical properties of hybrid fabrics in pultruded cement composites,” *Cem. Concr. Compos.*, vol. 31, no. 9, pp. 647–657, 2009, doi: 10.1016/j.cemconcomp.2009.06.002.
- [35] M. Kurban, O. Babaarslan, and İ. H. Çağatay, “Investigation of the flexural behavior of textile reinforced concrete with braiding yarn structure,” *Constr. Build. Mater.*, vol. 334, no. March, p. 127434, Jun. 2022, doi: 10.1016/j.conbuildmat.2022.127434.

- [36] E. Fehrer, “Engineered yarns with DREF friction spinning technology,” *Can. Text. J.*, vol. 104, no. 8, pp. 14–15, 1987.
- [37] M. Bar, R. Alagirusamy, and A. Das, “Properties of flax-polypropylene composites made through hybrid yarn and film stacking methods,” *Compos. Struct.*, vol. 197, pp. 63–71, Aug. 2018, doi: 10.1016/j.compstruct.2018.04.078.
- [38] V. Hanisch, A. Kolkman, A. Roye, and T. Gries, “Influence of machine settings on mechanical performance of yarn and textile structures,” in *ICTRC’2006 - 1st International RILEM Conference on Textile Reinforced Concrete*, 2006, pp. 13–22, doi: 10.1617/2351580087.002.
- [39] G. Plizzari and S. Mindess, “Fibre-reinforced concrete,” in *Developments in the Formulation and Reinforcement of Concrete*, Second., Elsevier, 2019, pp. 257–287.
- [40] A. E. Naaman, “Fibre reinforced concrete: five decades of progress,” in *Proceedings of the 4th Brazilian Conference on Composite Materials*, 2018, pp. 35–56, doi: 10.21452/bccm4.2018.02.01.
- [41] ACI Committee 544, “ACI PRC-544.1R-96: Report on Fibre Reinforced Concrete (Reapproved 2009),” American Concrete Institute, 2002. [Online]. Available: <https://books.google.fr/books?id=76mGZwEACAAJ>.
- [42] C. Zhao, Z. Wang, Z. Zhu, Q. Guo, X. Wu, and R. Zhao, “Research on different types of fibre reinforced concrete in recent years: An overview,” *Constr. Build. Mater.*, vol. 365, no. October 2022, p. 130075, Feb. 2023, doi: 10.1016/j.conbuildmat.2022.130075.
- [43] N. K. Barman, R. Alagirusamy, and S. S. Bhattacharya, “Flexible Towpregs and Thermoplastic Composites for Civil Engineering Applications,” in *Flexible Towpregs and Their Thermoplastic Composites*, First., R. Alagirusamy, Ed. Boca Raton: CRC Press, 2022, pp. 357–396.
- [44] A. E. Naaman, “Thin TRC products: Status, outlook, and future directions,” in *Textile Fibre Composites in Civil Engineering*, T. Triantafillou, Ed. Elsevier, 2016, pp. 413–439.
- [45] C. Aldea, T. Gries, and A. Roye, “Definition,” in *Textile Reinforced Concrete - State-*

- of-the-Art Report of RILEM TC 201-TRC*, W. Brameshuber, Ed. RILEM Publications SARL, 2006, pp. 5–9.
- [46] M. J. Islam, T. Ahmed, S. M. F. Bin Imam, H. Islam, and F. U. A. Shaikh, “Comparative study of carbon fibre and galvanized iron textile reinforced concrete,” *Constr. Build. Mater.*, vol. 374, no. March, p. 130928, Apr. 2023, doi: 10.1016/j.conbuildmat.2023.130928.
- [47] S. Paul, R. Gettu, D. Naidu Arnepalli, and R. Samanthula, “Experimental evaluation of the durability of glass Textile-Reinforced concrete,” *Constr. Build. Mater.*, vol. 406, no. May, p. 133390, Nov. 2023, doi: 10.1016/j.conbuildmat.2023.133390.
- [48] H. Thiyagarajan, R. Gopal, and S. Gopinath, “Textile Reinforced Concrete Subjected to Acidic and Alkaline Environment: Experimental Study,” *J. Mater. Civ. Eng.*, vol. 34, no. 8, Aug. 2022, doi: 10.1061/(ASCE)MT.1943-5533.0004307.
- [49] M. Hutaibat, B. Ghiassi, and W. Tizani, “Flexural behaviour of concrete thin sheets prestressed with basalt-textile reinforcement,” *Constr. Build. Mater.*, vol. 404, no. August, p. 133213, Nov. 2023, doi: 10.1016/j.conbuildmat.2023.133213.
- [50] A. Peled, S. Sueki, and B. Mobasher, “Bonding in fabric–cement systems: Effects of fabrication methods,” *Cem. Concr. Res.*, vol. 36, no. 9, pp. 1661–1671, Sep. 2006, doi: 10.1016/j.cemconres.2006.05.009.
- [51] K. Holschemacher, “Challenges in the Production of Carbon Reinforced Concrete,” in *Lecture Notes in Civil Engineering*, vol. 203, Springer Singapore, 2022, pp. 823–831.
- [52] W. Brameshuber, “Manufacturing methods for textile-reinforced concrete,” in *Textile Fibre Composites in Civil Engineering*, Elsevier, 2016, pp. 45–59.
- [53] P. Valeri, P. Guaita, R. Baur, M. Fernández Ruiz, D. Fernández- Ordóñez, and A. Muttoni, “Textile reinforced concrete for sustainable structures: Future perspectives and application to a prototype pavilion,” *Struct. Concr.*, vol. 21, no. 6, pp. 2251–2267, Dec. 2020, doi: 10.1002/suco.201900511.
- [54] E. Tsangouri, A. Van Driessche, G. Livitsanos, and D. G. Aggelis, “Design, casting and fracture analysis of textile reinforced cementitious shells,” *Dev. Built Environ.*, vol. 3, no. June, p. 100013, Aug. 2020, doi: 10.1016/j.dibe.2020.100013.

- [55] H. W. Reinhardt, M. Krüger, and C. U. Große, “Concrete Prestressed with Textile Fabric,” *J. Adv. Concr. Technol.*, vol. 1, no. 3, pp. 231–239, 2003, doi: 10.3151/jact.1.231.
- [56] S. Gopinath, R. Gettu, and N. R. Iyer, “Influence of prestressing the textile on the tensile behaviour of textile reinforced concrete,” *Mater. Struct.*, vol. 51, no. 3, p. 64, Jun. 2018, doi: 10.1617/s11527-018-1194-z.
- [57] A. Peled, “Pre-tensioning of fabrics in cement-based composites,” *Cem. Concr. Res.*, vol. 37, no. 5, pp. 805–813, May 2007, doi: 10.1016/j.cemconres.2007.02.010.
- [58] K. Zdanowicz, B. Schmidt, H. Naraniecki, and S. Marx, “Bond behaviour of chemically prestressed textile reinforced concrete,” in *IABSE Symposium, Guimaraes 2019: Towards a Resilient Built Environment Risk and Asset Management - Report*, 2019, no. March, pp. 297–303, doi: 10.2749/guimaraes.2019.0297.
- [59] J. Park, S.-K. Park, and S. Hong, “Experimental Study of Flexural Behavior of Reinforced Concrete Beam Strengthened with Prestressed Textile-Reinforced Mortar,” *Materials (Basel)*, vol. 13, no. 5, p. 1137, Mar. 2020, doi: 10.3390/ma13051137.
- [60] W. Brameshuber *et al.*, “Production technologies,” in *Textile Reinforced Concrete - State-of-the-Art Report of RILEM TC 201-TRC*, W. Brameshuber, Ed. RILEM Publications SARL, 2006, pp. 57–81.
- [61] I. G. Colombo, A. Magri, G. Zani, M. Colombo, and M. di Prisco, “Erratum to: Textile Reinforced Concrete: experimental investigation on design parameters,” *Mater. Struct.*, vol. 46, no. 11, pp. 1953–1971, Nov. 2013, doi: 10.1617/s11527-013-0023-7.
- [62] I. Galan, A. Baldermann, W. Kusterle, M. Dietzel, and F. Mittermayr, “Durability of shotcrete for underground support– Review and update,” *Constr. Build. Mater.*, vol. 202, pp. 465–493, Mar. 2019, doi: 10.1016/j.conbuildmat.2018.12.151.
- [63] C0050600, *ACI PRC-506-16 Guide to Shotcrete*. Farmington Hills, MI: American Concrete Institute, 2016.
- [64] B. Mobasher and A. Pivacek, “A filament winding technique for manufacturing cement based cross-ply laminates,” *Cem. Concr. Compos.*, vol. 20, no. 5, pp. 405–415, Oct. 1998, doi: 10.1016/S0958-9465(98)00011-0.

- [65] A. Peled and B. Mobasher, "Properties of Fabric–Cement Composites made by Pultrusion," *Mater. Struct.*, vol. 39, no. 8, pp. 787–797, Oct. 2006, doi: 10.1617/s11527-006-9171-3.
- [66] A. Peled and B. Mobasher, "Pultruded Fabric-Cement Composites," *ACI Mater. J.*, vol. 102, no. 1, pp. 15–23, 2005.
- [67] E. Haim and A. Peled, "Impact Behavior of Textile and Hybrid Cement-Based Composites," *ACI Mater. J.*, vol. 108, no. 3, pp. 235–243, 2011.
- [68] A. Peled and B. Mobasher, "Tensile Behavior of Fabric Cement-Based Composites: Pultruded and Cast," *J. Mater. Civ. Eng.*, vol. 19, no. 4, pp. 340–348, Apr. 2007, doi: 10.1061/(ASCE)0899-1561(2007)19:4(340).
- [69] H. Kloft, M. Empelmann, N. Hack, E. Herrmann, and D. Lowke, "Reinforcement strategies for 3D- concrete- printing," *Civ. Eng. Des.*, vol. 2, no. 4, pp. 131–139, Aug. 2020, doi: 10.1002/cend.202000022.
- [70] N. Hack *et al.*, "Development of a Robot-Based Multi-Directional Dynamic Fibre Winding Process for Additive Manufacturing Using Shotcrete 3D Printing," *Fibres*, vol. 9, no. 6, p. 39, Jun. 2021, doi: 10.3390/fib9060039.
- [71] R. Alagirusamy, R. Fanguero, V. Ogale, and N. Padaki, "Hybrid Yarns and Textile Preforming for Thermoplastic Composites," *Text. Prog.*, vol. 38, no. 4, pp. 1–71, Jan. 2006, doi: 10.1533/tepr.2006.0004.
- [72] R. Alagirusamy and V. Ogale, "Commingled and Air Jet-textured Hybrid Yarns for Thermoplastic Composites," *J. Ind. Text.*, vol. 33, no. 4, pp. 223–243, Apr. 2004, doi: 10.1177/1528083704044360.
- [73] B. Lauke, U. Bunzel, and K. Schneider, "Effect of hybrid yarn structure on the delamination behaviour of thermoplastic composites," *Compos. Part A Appl. Sci. Manuf.*, vol. 29, no. 11, pp. 1397–1409, 1998, doi: 10.1016/S1359-835X(98)00059-1.
- [74] R. Alagirusamy and V. Ogale, "Development and Characterization of GF/PET, GF/Nylon, and GF/PP Commingled Yarns for Thermoplastic Composites," *J. Thermoplast. Compos. Mater.*, vol. 18, no. 3, pp. 269–285, May 2005, doi: 10.1177/0892705705049557.

- [75] J. Bernhardsson and R. Shishoo, “Effect of Processing Parameters on Consolidation Quality of GF/PP Commingled Yarn Based Composites,” *J. Thermoplast. Compos. Mater.*, vol. 13, no. 4, pp. 292–313, Jul. 2000, doi: 10.1177/089270570001300403.
- [76] E. Mäder, J. Rausch, and N. Schmidt, “Commingled yarns – Processing aspects and tailored surfaces of polypropylene/glass composites,” *Compos. Part A Appl. Sci. Manuf.*, vol. 39, no. 4, pp. 612–623, Apr. 2008, doi: 10.1016/j.compositesa.2007.07.011.
- [77] N. Wiegand and E. Mäder, “Commingled Yarn Spinning for Thermoplastic/Glass Fibre Composites,” *Fibres*, vol. 5, no. 3, p. 26, Jul. 2017, doi: 10.3390/fib5030026.
- [78] B.-D. Choi, O. Diestel, and P. Offermann, “Commingled CF/PEEK Hybrid Yarns for Use in Textile Reinforced High Performance Rotors,” in *12th International Conference on Composite Materials (ICCM)*, 1999, pp. 796–806, [Online]. Available: <http://www.iccm-central.org/Proceedings/ICCM12proceedings/site/papers/pap528.pdf>.
- [79] J. P. Nunes, J. F. Silva, and P. J. Novo, “PROCESSING THERMOPLASTIC MATRIX TOWPREGS BY PULTRUSION,” *Adv. Polym. Technol.*, vol. 32, no. S1, pp. E306–E312, Mar. 2013, doi: 10.1002/adv.21279.
- [80] V. Goud, R. Alagirusamy, A. Das, and D. Kalyanasundaram, “Dry Electrostatic Spray Coated Towpregs for Thermoplastic Composites,” *Fibres Polym.*, vol. 19, no. 2, pp. 364–374, Feb. 2018, doi: 10.1007/s12221-018-7470-7.
- [81] V. Goud, A. Ramasamy, A. Das, and D. Kalyanasundaram, “Box-Behnken technique based multi-parametric optimization of electrostatic spray coating in the manufacturing of thermoplastic composites,” *Mater. Manuf. Process.*, vol. 34, no. 14, pp. 1638–1645, Oct. 2019, doi: 10.1080/10426914.2019.1666991.
- [82] V. Goud, R. Alagirusamy, A. Das, and D. Kalyanasundaram, “Influence of various forms of polypropylene matrix (fibre, powder and film states) on the flexural strength of carbon-polypropylene composites,” *Compos. Part B Eng.*, vol. 166, no. May 2018, pp. 56–64, Jun. 2019, doi: 10.1016/j.compositesb.2018.11.135.
- [83] V. Goud, R. Alagirusamy, and A. Das, “Towpreg Manufacturing Techniques,” in *Flexible Towpregs and Their Thermoplastic Composites*, First., R. Alagirusamy, Ed. Boca Raton: CRC Press, 2022, pp. 33–58.

- [84] M. Bar, “Studies on natural fibre based twist-less hybrid yarn reinforced thermoplastic composites,” Indian Institute of Technology Delhi, 2018.
- [85] C. Ayranci and J. Carey, “2D braided composites: A review for stiffness critical applications,” *Compos. Struct.*, vol. 85, no. 1, pp. 43–58, Sep. 2008, doi: 10.1016/j.compstruct.2007.10.004.
- [86] Y. Kyosev, *Braiding Technology for Textiles*. Elsevier, 2015.
- [87] K. Birkefeld, M. Röder, T. von Reden, M. Bulat, and K. Drechsler, “Characterization of Biaxial and Triaxial Braids: Fibre Architecture and Mechanical Properties,” *Appl. Compos. Mater.*, vol. 19, no. 3–4, pp. 259–273, Jun. 2012, doi: 10.1007/s10443-011-9190-2.
- [88] Z. T. Kier, A. Salvi, G. Theis, A. M. Waas, and K. Shahwan, “Estimating mechanical properties of 2D triaxially braided textile composites based on microstructure properties,” *Compos. Part B Eng.*, vol. 68, pp. 288–299, Jan. 2015, doi: 10.1016/j.compositesb.2014.08.039.
- [89] L. Zhang and M. Miao, “Commingled natural fibre/polypropylene wrap spun yarns for structured thermoplastic composites,” *Compos. Sci. Technol.*, vol. 70, no. 1, pp. 130–135, 2010, doi: 10.1016/j.compscitech.2009.09.016.
- [90] O. A. Khondker, U. S. Ishiaku, A. Nakai, and H. Hamada, “A novel processing technique for thermoplastic manufacturing of unidirectional composites reinforced with jute yarns,” *Compos. Part A Appl. Sci. Manuf.*, vol. 37, no. 12, pp. 2274–2284, Dec. 2006, doi: 10.1016/j.compositesa.2005.12.030.
- [91] M. A. Kaddaha, R. Younes, and P. Lafon, “New Geometrical Modelling for 2D Fabric and 2.5D Interlock Composites,” *Textiles*, vol. 2, no. 1, pp. 142–161, Mar. 2022, doi: 10.3390/textiles2010008.
- [92] K. L. Gandhi and W. S. Sondhelm, “Technical fabric structures – 1. Woven fabrics,” in *Handbook of Technical Textiles*, Second., R. A. Horrocks and S. C. Anand, Eds. Woodhead Publishing, 2016, pp. 63–106.
- [93] D. Weise, M. Vorhof, R. Brünler, C. Sennewald, G. Hoffmann, and C. Cherif, “Reduction of weaving process-induced warp yarn damage and crimp of leno scrim

- based on coarse high-performance fibres,” *Text. Res. J.*, vol. 89, no. 16, pp. 3326–3341, Aug. 2019, doi: 10.1177/0040517518809049.
- [94] A. Peled, A. Bentur, and D. Yankelevsky, “Flexural Performance of Cementitious Composites Reinforced with Woven Fabrics,” *J. Mater. Civ. Eng.*, vol. 11, no. 4, pp. 325–330, Nov. 1999, doi: 10.1061/(ASCE)0899-1561(1999)11:4(325).
- [95] M. Halvaei, M. Jamshidi, M. Latifi, and M. Ejtemaei, “Experimental investigation and modelling of flexural properties of carbon textile reinforced concrete,” *Constr. Build. Mater.*, vol. 262, p. 120877, Nov. 2020, doi: 10.1016/j.conbuildmat.2020.120877.
- [96] N. K. Barman, A. Ramasamy, and S. S. Bhattacharya, “Improving performance of concrete structures with textile reinforcements,” in *Emerging Trends in Traditional and Technical Textiles-Select Proceedings of ICETT 2023*, 2024.
- [97] D. Zhu, A. Peled, and B. Mobasher, “Dynamic tensile testing of fabric–cement composites,” *Constr. Build. Mater.*, vol. 25, no. 1, pp. 385–395, Jan. 2011, doi: 10.1016/j.conbuildmat.2010.06.014.
- [98] S. Gopinath, A. Prakash, R. Aahrthy, and M. B. Harish, “Investigations on the influence of matrix and textile on the response of textile reinforced concrete slabs under impact loading,” *Sadhana - Acad. Proc. Eng. Sci.*, vol. 43, no. 11, 2018, doi: 10.1007/s12046-018-0933-8.
- [99] M. Zargaran, N. K. A. Attari, S. Alizadeh, and P. Teymouri, “Minimum reinforcement ratio in TRC panels for deflection hardening flexural performance,” *Constr. Build. Mater.*, vol. 137, pp. 459–469, Apr. 2017, doi: 10.1016/j.conbuildmat.2017.01.091.
- [100] P. Teymouri, M. Zargaran, and N. K. A. Attari, “Special Nylon Fabric as a New Material for Reinforcing Cement Composite,” *Adv. Mater. Res.*, vol. 772, pp. 167–172, Sep. 2013, doi: 10.4028/www.scientific.net/AMR.772.167.
- [101] F. Schladitz, M. Frenzel, D. Ehlig, and M. Curbach, “Bending load capacity of reinforced concrete slabs strengthened with textile reinforced concrete,” *Eng. Struct.*, vol. 40, pp. 317–326, Jul. 2012, doi: 10.1016/j.engstruct.2012.02.029.
- [102] A. Bentur, A. Peled, and D. Yankelevsky, “ENHANCED BONDING OF LOW MODULUS POLYMER FIBRES-CEMENT MATRIX BY MEANS OF CRIMPED

- GEOMETRY,” *Cem. Concr. Res.*, vol. 27, no. 7, pp. 1099–1111, Jul. 1997, doi: 10.1016/S0008-8846(97)00088-4.
- [103] A. Peled, “Textiles as reinforcements for cement composites under impact loading,” in *Fifth International RILEM Workshop on High Performance Fibre Reinforced Cement Composites (HPFRCC5)*, 2007, pp. 455–462.
- [104] M. A. Al-Monsur, G. Bardl, and C. Cherif, “Evaluation of adhesive binders for the development of yarn bonding for new stitch-free non-crimp fabrics,” *Text. Res. J.*, vol. 85, no. 15, pp. 1635–1648, Sep. 2015, doi: 10.1177/0040517514566111.
- [105] L. Hahn, S. Rittner, C. Bauer, and C. Cherif, “Development of alternative bondings for the production of stitch-free non-crimp fabrics made of multiple carbon fibre heavy tows for construction industry,” *J. Ind. Text.*, vol. 48, no. 3, pp. 660–681, Sep. 2018, doi: 10.1177/1528083717736100.
- [106] M. K. Dolatabadi, S. Janetzko, and T. Gries, “Geometrical and mechanical properties of a non-crimp fabric applicable for textile reinforced concrete,” *J. Text. Inst.*, vol. 105, no. 7, pp. 711–716, Jul. 2014, doi: 10.1080/00405000.2013.844908.
- [107] R. Böhm, M. Thieme, D. Wohlfahrt, D. Wolz, B. Richter, and H. Jäger, “Reinforcement Systems for Carbon Concrete Composites Based on Low-Cost Carbon Fibres,” *Fibres*, vol. 6, no. 3, p. 56, Aug. 2018, doi: 10.3390/fib6030056.
- [108] E. Zdraveva, C. Gonilho-Pereira, R. Figueiro, S. Lanceros-Méndez, S. Jalali, and M. Araújo, “Multifunctional Braided Composite Rods for Civil Engineering Applications,” *Adv. Mater. Res.*, vol. 123–125, pp. 149–152, Aug. 2010, doi: 10.4028/www.scientific.net/AMR.123-125.149.
- [109] L. Correia, F. Cunha, P. Subramani, and R. Figueiro, “DEVELOPMENT OF HYBRID BRAIDED COMPOSITE RODS WITH HIGH DUCTILITY FOR CIVIL ENGINEERING,” in *Proceedings of the 5th International Conference on Integrity-Reliability-Failure*, 2016, no. July, pp. 305–306.
- [110] C. Gonilho Pereira, R. Figueiro, S. Jalali, M. Araújo, and P. Marques, “Braided reinforced composite rods for the internal reinforcement of concrete,” *Mech. Compos. Mater.*, vol. 44, no. 3, pp. 221–230, May 2008, doi: 10.1007/s11029-008-9015-z.

- [111] N. F. Grace, W. F. Ragheb, and G. Abdel-Sayed, “Development and application of innovative triaxially braided ductile FRP fabric for strengthening concrete beams,” *Compos. Struct.*, vol. 64, no. 3–4, pp. 521–530, Jun. 2004, doi: 10.1016/j.compstruct.2003.09.051.
- [112] N. F. Grace, W. F. Ragheb, and G. Abdel-Sayed, “Innovative Triaxially Braided Ductile FRP Fabric for Strengthening Structures,” in *SP-230: 7th International Symposium on Fibre-Reinforced (FRP) Polymer Reinforcement for Concrete Structures*, 2005, vol. SP-230, pp. 119–134, doi: 10.14359/14828.
- [113] K. P. Rosado, S. Rana, C. Pereira, and R. Figueiro, “Self-Sensing Hybrid Composite Rod with Braided Reinforcement for Structural Health Monitoring,” *Mater. Sci. Forum*, vol. 730–732, pp. 379–384, Nov. 2012, doi: 10.4028/www.scientific.net/MSF.730-732.379.
- [114] F. Cunha, D. Oliveira, G. Vasconcelos, and R. Figueiro, “Applications of Braided Structures in Civil Engineering,” in *Braided Structures and Composites: Production, Properties, Mechanics, and Technical Applications*, First., S. Rana and R. Figueiro, Eds. Boca Raton: CRC Press, 2015, pp. 195–230.
- [115] S. Rana, E. Zdraveva, C. Pereira, R. Figueiro, and A. G. Correia, “Development of Hybrid Braided Composite Rods for Reinforcement and Health Monitoring of Structures,” *Sci. World J.*, vol. 2014, pp. 1–9, 2014, doi: 10.1155/2014/170187.
- [116] C. Li, R. Guo, G. Xian, and H. Li, “Effects of elevated temperature, hydraulic pressure and fatigue loading on the property evolution of a carbon/glass fibre hybrid rod,” *Polym. Test.*, vol. 90, no. July, pp. 1–13, Oct. 2020, doi: 10.1016/j.polymertesting.2020.106761.
- [117] C. Li, X. Yin, Y. Liu, R. Guo, and G. Xian, “Long-term service evaluation of a pultruded carbon/glass hybrid rod exposed to elevated temperature, hydraulic pressure and fatigue load coupling,” *Int. J. Fatigue*, vol. 134, no. September 2019, pp. 1–15, May 2020, doi: 10.1016/j.ijfatigue.2020.105480.
- [118] C. Li *et al.*, “Mechanical property evolution and service life prediction of pultruded carbon/glass hybrid rod exposed in harsh oil-well condition,” *Compos. Struct.*, vol. 246, no. March, pp. 1–12, Aug. 2020, doi: 10.1016/j.compstruct.2020.112418.

- [119] C. M. Pastore and F. K. Ko, “Braided Hybrid Composites for Bridge Repair, National Textile Center Annual Report, Project No: F98-P01,” Philadelphia, 1999. [Online]. Available: <https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.384.8066&rep=rep1&type=pdf>.
- [120] F. K. Ko, W. Somboonsong, and H. G. Harris, “Fibre Architecture Based Design of Ductile Composite Rebar for Concrete Structures,” in *Proceedings of ICCM-11: International Conference on Composite Materials*, 1997, no. July, pp. 723–730, [Online]. Available: http://www.iccm-central.org/Proceedings/ICCM11proceedings/papers/ICCM11_V6_76.pdf.
- [121] H. G. Harris, W. Somboonsong, and F. K. Ko, “New Ductile Hybrid FRP Reinforcing Bar for Concrete Structures,” *J. Compos. Constr.*, vol. 2, no. 1, pp. 28–37, Feb. 1998, doi: 10.1061/(ASCE)1090-0268(1998)2:1(28).
- [122] D. Y. Moon, J. Sim, and H. Oh, “Experimental characterization of the bond performance of a new type of glass fibre-reinforced polymer rebar for application in concrete structures,” *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.*, vol. 221, no. 2, pp. 113–119, Apr. 2007, doi: 10.1243/14644207JMDA109.
- [123] J.-P. Won, C.-G. Park, and C.-I. Jang, “Tensile Fracture and Bond Properties of Ductile Hybrid FRP Reinforcing Bars,” *Polym. Polym. Compos.*, vol. 15, no. 1, pp. 9–16, Jan. 2007, doi: 10.1177/096739110701500102.
- [124] M. Glowania, T. Gries, J. Schoene, M. Schleser, and U. Reisgen, “Innovative Coating Technology for Textile Reinforcements of Concrete Applications,” *Key Eng. Mater.*, vol. 466, pp. 167–173, Jan. 2011, doi: 10.4028/www.scientific.net/KEM.466.167.
- [125] P. Valeri, M. Fernández Ruiz, and A. Muttoni, “Tensile response of textile reinforced concrete,” *Constr. Build. Mater.*, vol. 258, p. 119517, Oct. 2020, doi: 10.1016/j.conbuildmat.2020.119517.
- [126] M. Scheurer, M. Kalthoff, T. Matschei, M. Raupach, and T. Gries, “Analysis of Curing and Mechanical Performance of Pre-Impregnated Carbon Fibres Cured within Concrete,” *Textiles*, vol. 2, no. 4, pp. 657–672, Dec. 2022, doi: 10.3390/textiles2040038.

- [127] V. Mechtcherine, A. Michel, M. Liebscher, K. Schneider, and C. Großmann, “Mineral-impregnated carbon fibre composites as novel reinforcement for concrete construction: Material and automation perspectives,” *Autom. Constr.*, vol. 110, no. March 2019, p. 103002, Feb. 2020, doi: 10.1016/j.autcon.2019.103002.
- [128] K. Schneider, A. Michel, M. Liebscher, L. Terreri, S. Hempel, and V. Mechtcherine, “Mineral-impregnated carbon fibre reinforcement for high temperature resistance of thin-walled concrete structures,” *Cem. Concr. Compos.*, vol. 97, pp. 68–77, Mar. 2019, doi: 10.1016/j.cemconcomp.2018.12.006.
- [129] H. Li *et al.*, “Electrochemical modification of carbon fibre yarns in cementitious pore solution for an enhanced interaction towards concrete matrices,” *Appl. Surf. Sci.*, vol. 487, no. November 2018, pp. 52–58, Sep. 2019, doi: 10.1016/j.apsusc.2019.04.246.
- [130] J. Zhao *et al.*, “Development and testing of fast curing, mineral-impregnated carbon fibre (MCF) reinforcements based on metakaolin-made geopolymers,” *Cem. Concr. Compos.*, vol. 116, p. 103898, Feb. 2021, doi: 10.1016/j.cemconcomp.2020.103898.
- [131] K. Schneider *et al.*, “Mineral-Based Coating of Plasma-Treated Carbon Fibre Rovings for Carbon Concrete Composites with Enhanced Mechanical Performance,” *Materials (Basel)*, vol. 10, no. 4, p. 360, Mar. 2017, doi: 10.3390/ma10040360.
- [132] C. Scheffler *et al.*, “Interphase modification of alkali-resistant glass fibres and carbon fibres for textile reinforced concrete I: Fibre properties and durability,” *Compos. Sci. Technol.*, vol. 69, no. 3–4, pp. 531–538, 2009, doi: 10.1016/j.compscitech.2008.11.027.
- [133] S. L. Gao, E. Mäder, and R. Plonka, “Coatings for glass fibres in a cementitious matrix,” *Acta Mater.*, vol. 52, no. 16, pp. 4745–4755, Sep. 2004, doi: 10.1016/j.actamat.2004.06.028.
- [134] U. Koeckritz, C. Cherif, S. Weiland, and M. Curbach, “In-situ polymer coating of open grid warp knitted fabrics for textile reinforced concrete application,” *J. Ind. Text.*, vol. 40, no. 2, pp. 157–169, 2010, doi: 10.1177/1528083709102938.
- [135] O. Weichold and M. Möller, “A Cement-in-Poly(Vinyl Alcohol) Dispersion for Improved Fibre-Matrix Adhesion in Continuous Glass-Fibre Reinforced Concrete,” *Adv. Eng. Mater.*, vol. 9, no. 8, pp. 712–715, Aug. 2007, doi:

10.1002/adem.200700113.

- [136] S. Tyagi, J. Y. Lee, G. A. Buxton, and A. C. Balazs, “Using Nanocomposite Coatings To Heal Surface Defects,” *Macromolecules*, vol. 37, no. 24, pp. 9160–9168, Nov. 2004, doi: 10.1021/ma048773l.
- [137] O. Weichold, “Preparation and properties of hybrid cement-in-polymer coatings used for the improvement of fibre-matrix adhesion in textile reinforced concrete,” *J. Appl. Polym. Sci.*, vol. 116, no. 6, p. NA-NA, 2010, doi: 10.1002/app.31815.
- [138] A. Pourasee, A. Peled, and J. Weiss, “Fluid transport in cracked fabric-reinforced-cement-based composites,” *J. Mater. Civ. Eng.*, vol. 23, no. 8, pp. 1227–1238, 2011, doi: 10.1061/(ASCE)MT.1943-5533.0000289.
- [139] M. Lieboldt and V. Mechtcherine, “Capillary transport of water through textile-reinforced concrete applied in repairing and/or strengthening cracked RC structures,” *Cem. Concr. Res.*, vol. 52, pp. 53–62, 2013, doi: 10.1016/j.cemconres.2013.05.012.
- [140] H. H. Pham, N. H. Dinh, S. Kim, S. Park, and K.-K. Choi, “Tensile behavioral characteristics of lightweight carbon textile-reinforced cementitious composites,” *J. Build. Eng.*, vol. 57, no. April, p. 104848, Oct. 2022, doi: 10.1016/j.job.2022.104848.
- [141] M. El-Messiry, S. El-Tarfawy, and R. El Deeb, “Enhanced impact properties of cementitious composites reinforced with pultruded flax/polymeric matrix fabric,” *Alexandria Eng. J.*, vol. 56, no. 3, pp. 297–307, Sep. 2017, doi: 10.1016/j.aej.2017.03.032.
- [142] R. Barhum and V. Mechtcherine, “Effect of short, dispersed glass and carbon fibres on the behaviour of textile-reinforced concrete under tensile loading,” *Eng. Fract. Mech.*, vol. 92, pp. 56–71, Sep. 2012, doi: 10.1016/j.engfracmech.2012.06.001.
- [143] Y. Ding, Q. Wang, F. Pacheco-Torgal, and Y. Zhang, “Hybrid effect of basalt fibre textile and macro polypropylene fibre on flexural load-bearing capacity and toughness of two-way concrete slabs,” *Constr. Build. Mater.*, vol. 261, pp. 1–11, Nov. 2020, doi: 10.1016/j.conbuildmat.2020.119881.
- [144] H. R. Pakravan, M. Jamshidi, and H. Rezaei, “Effect of textile surface treatment on the flexural properties of textile-reinforced cementitious composites,” *J. Ind. Text.*, vol.

- 46, no. 1, pp. 116–129, Jul. 2016, doi: 10.1177/1528083715576320.
- [145] M. Deng, Z. Dong, and C. Zhang, “Experimental investigation on tensile behavior of carbon textile reinforced mortar (TRM) added with short polyvinyl alcohol (PVA) fibres,” *Constr. Build. Mater.*, vol. 235, pp. 1–12, Feb. 2020, doi: 10.1016/j.conbuildmat.2019.117801.
- [146] A. Peled and A. Bentur, “Quantitative Description of the Pull-Out Behavior of Crimped Yarns from Cement Matrix,” *J. Mater. Civ. Eng.*, vol. 15, no. 6, pp. 537–544, 2003, doi: 10.1061/(asce)0899-1561(2003)15:6(537).
- [147] E. Lorenz and R. Ortlepp, “Bond Behavior of Textile Reinforcements - Development of a Pull-Out Test and Modeling of the Respective Bond versus Slip Relation,” in *High Performance Fibre Reinforced Cement Composites*, vol. 2, no. June, G. J. Parra-Montesinos, H. W. Reinhardt, and A. E. Naaman, Eds. Dordrecht: Springer Netherlands, 2012, pp. 479–486.
- [148] N. Williams Portal, I. Fernandez Perez, L. Nyholm Thrane, and K. Lundgren, “Pull-out of textile reinforcement in concrete,” *Constr. Build. Mater.*, vol. 71, pp. 63–71, Nov. 2014, doi: 10.1016/j.conbuildmat.2014.08.014.
- [149] B. H. Tekle, D. Messerer, and K. Holschemacher, “Bond induced concrete splitting failure in textile-reinforced fine-grained concrete,” *Constr. Build. Mater.*, vol. 303, no. August, p. 124503, Oct. 2021, doi: 10.1016/j.conbuildmat.2021.124503.

