Glass Fibre Reinforced Polymer Reinforcement for Offshore Concrete Structures

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Offshore Concrete Structures

- Corrosion of steel reinforcement in marine conditions
- Stainless steel- expensive
- Steel market price fluctuations

Can non-metallic rebar provide a better solution?

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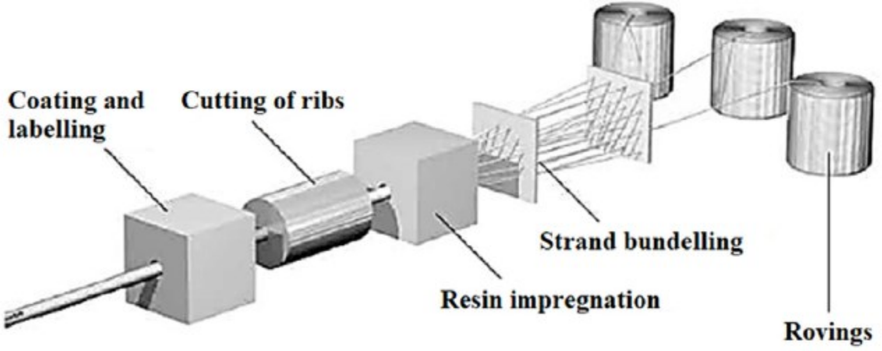
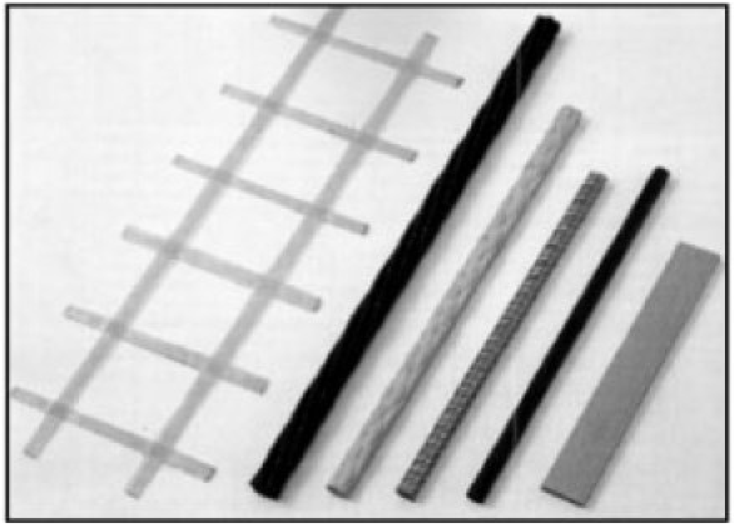
Fibre Reinforced Polymer (FRP) Rebar Technologies

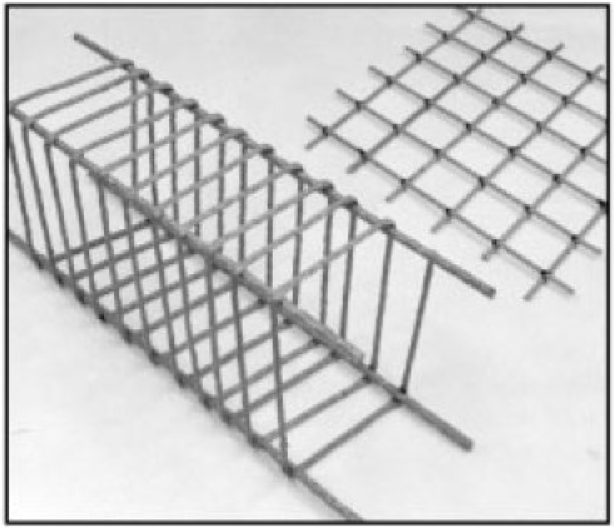


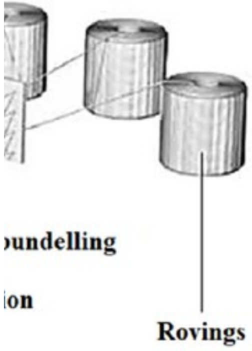
Pultrusion Process for FRP Rebar

https://doi.org/10.1016/j.cemconcomp.2022.104758

Fibre Reinforced Polymer (FRP) Rebar Technologies







ebar

(c) AFRP (d) BFRP

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Fibre Reinforced Polymer (FRP) Rebar Technologies

Table 1. Physical and mechanical properties of different FRPs

Type of FRP	Density	Tensile strength	Deformation modulus	Elongation	Coefficient of thermal expansion	Poisson's ratio
	kg/m^3	MPa	GPa	%	10^{-6}/°C	
Electrical-resistant *E*-glass	2500	3450	72.4	2.4	5.0	0.22
High-strength *S*-glass	2500	4580	85.5	3.3	2.9	0.22
Alkali-resistant *AR*-glass	2270	1800–3500	70–76	2.0–3.0	n/a	n/a
Carbon	1700	3700	250	1.2	–0.6 up to –0.2	0.20
Carbon (high-modulus)	1950	2500–4000	350–800	0.5	–1.2 up to –0.1	0.20
Carbon (high-strength)	1750	4800	240	1.1	–0.6 up to –0.2	0.20
Aramid (Kevlar 29)	1440	2760	62	4.4	–2.0 longitudinal 59 radial	0.35
Aramid (Kevlar 49)	1440	3620	124	2.2	–2.0 longitudinal 59 radial	0.35
Aramid (Kevlar 149)	1440	3450	175	1.4	–2.0 longitudinal 59 radial	0.35
Aramid (Technora H)	1390	3000	70	4.4	–2.0 longitudinal 59 radial	0.35
Aramid (SVM)	1430	3800–4200	130	3.5	n/a	n/a
Bazalt (Albarrie)	2800	4840	89	3.1	8.0	n/a

GFRP bars are the most widely used- less expensive than the others, already matured technology

doi:10.3846/2029882X.2014.889274

Fibre Reinforced Polymer (FRP) Rebar Technologies

Key advantages of the GFRP Rebars

1. Excellent corrosion resistance
2. Thermal expansion coefficient close to that of concrete
3. Significantly lighter weight than steel (high strength to weight ratio)
4. Excellent fatigue performance
5. Electrically non-conductive
6. High impact resistance
7. Transparent to magnetic fields

Fibre Reinforced Polymer (FRP) Rebar- Current Status

Table 5—Production Schedule of the FRP rebar Manufacturers

Manufacturer	First GFRP bars Year	Production Approach	Production Rate m/d	ft/d
AFR	2013	Stock in large quantities	684	2.244
ASL	1993	Stock in large quantities	12.200	40.000
KOD	1984	N/A	N/A	N/A
MAR	1995	Stock in large quantities	9.150	30.000
NEU	2014	Production on demand	7.925	26.000
SUD	N/A	Stock in large quantities	N/A	N/A
RAW	1988	Production on demand	4.575	15.000
PAL	N/A	Stock in large quantities	30.000	98.425
BBM	2013	Production on demand	3.000	9.845
BPC	2007	Stock in small quantities	N/A	N/A
ATP	1985	Production on demand	7.000	22.965
SIR	1992	Production on demand	15.000	49.215
FIX	1980	N/A	N/A	N/A
FIR	2004	Production on demand	9.000	29.528
ARM	2007	N/A	N/A	N/A
ARO	1990	N/A	N/A	N/A
PUN	1985	Production on demand	10.000	32.810
ARC	2003	N/A	N/A	N/A
CSK	2008	N/A	N/A	N/A
DXT	1997	N/A	N/A	N/A
CHK	2012	Stock in large quantities	40.000	131.234
GBF	2003	N/A	N/A	N/A

Table 3—Location of FRP rebar manufacturers

Manufacturer			Location of the Headquarters		
No.	ID	Name	Country	State	City
1	AFR	American Fiberglass Rebar	USA	Nevada	Henderson
2	CRT	Composite Rebar Technologies, Inc.	USA	Wisconsin	Madison
3	ASL	Aslan, Hughes Brothers, Inc.	USA	Nebraska	Seward
4	KOD	Kodiak Fiberglass Rebar	USA	Texas	Huston
5	MAR	Marshall Composite Technologies, LLC	USA	Oregon	Salem
6	RAW	Raw Energy Materials Corporation	USA	Florida	Pompano Beach
7	NEU	Neuvokas	USA	Michigan	Ahmeek
8	SUD	Sudaglass Fiber Technology, Inc.	USA	Texas	Houston
9	SMS	Smarter Building Systems	USA	Rhode Island	Newport
10	PAL	Pultrall, Inc.	Canada	Quebec	Thetford Mines
11	BBM	B&B FRP Manufacturing Inc.	Canada	Ontario	Toronto
12	BPC	BP Composites, Ltd.	Canada	Alberta	Edmonton
13	ATP	ATP srl	Italy	Salerno	Angri
14	SIR	Sireg Geotech Srl	Italy	Milan	Arcore
15	FIX	Fibrolux GmbH	Germany	Hesse	Hofheim
16	SCH	Schoeck Bauteile	Germany	Baden-Wurtemberg	Baden-Baden
17	FIR	Firep Inc.	Switzerland	St. Gallen	Rapperswil
18	ARM	Armastek	Czech Republic	Prague	Prague
19	TEC	Technobasalt-Invest	Ukraine	Kiev	Kiev
20	ARO	Applied Research of Australia (AROA)	Australia	South Australia	Edinburgh North
21	PUN	Pultron Composites	New Zealand	Gisborne	Gisborne
22	ARC	ARC Insulations & Insulators (P) LTD.	India	West Bengal	Bishnupur
23	CSK	CSK Technologies	India	Telangana	Hyderabad
24	DXT	Dextra Group	Thailand	Bangkok	Bangkok
25	CHK	Composite Group Chelyabinsk	Russia	Chelyabinsk Region	Chelyabinsk
26	AFJ	Al-Afraj Group	Saudi Arabia	Eastern Province	Al-Khobar
27	GBF	Zhejiang GBF Basalt Fiber Co.	China	Zhejiang	Hangzhou

Ruiz Emparanza, Alvaro & Kampmann, Raphael & De Caso y Basalo, Francisco. (2017). State-of-the-Practice of Global Manufacturing of FRP Rebar and Specifications.

Fibre Reinforced Polymer (FRP) Rebar- Current Status

Table 4—FRP rebars products as produced by different manufacturers

Manufacturer	Fiber Type	Type of Cross Section	Surface Enhancement	Range of Rebar Sizes
AFR	Glass	●	Helical wrap + sand coat	# 2 – # 10
CRT	Glass	○	Ribs	N/A
ASL	Glass	●	Helical wrap + sand coat	# 2 – # 13
KOD	Glass/Basalt	●	Helical wrap + sand coat	# 2 – # 9
MAR	Glass	●	Ribs	# 3 – # 6
RAW	Glass	●	Helical wrap + sand coat	# 2 – # 10
NEU	Basalt	●	Sand coat	# 3
SUD	Basalt	●	Helical wrap	# 3 – # 8
SMS	Basalt	●	Helical wrap	# 2 – # 8
PAL	Glass	● Y	Sand coat	# 2 – # 18
BBM	Glass	●	Ribs	# 2 – # 10
BPC	Glass	●	Helical wrap + sand coat	# 3 – # 8
ATP	Glass	● ⬬	Helical wrap + sand coat	# 3 – # 11
SIR	Glass	● ⬬ ■ ○ ⬭ □ Y	Sand coat	# 1 – # 12
FIX	Glass	●	Helical wrap	N/A
SCH	Glass	●	Ribs	# 3 – # 10
FIR	Glass	●	Helical wrap + sand coat	N/A
ARM	Glass	●	Helical wrap	N/A
TEC	Basalt	●	Helical wrap	N/A
ARO	Glass	●	Ribs	N/A
PUN	Glass	● ○	Ribs	# 2 – # 13
ARC	Glass	●	N/A	N/A
CSK	Glass	●	N/A	N/A
DXT	Glass	●	Helical wrap + sand coat	# 2 – # 16
CHK	Glass	●	Helical wrap + sand coat	# 2 – # 18
AFJ	Glass	●	N/A	N/A
GBF	Basalt	●	N/A	# 2 – # 8

● Round solid; ⬬ Oval solid; ■ Quadratic solid; ○ Round hollow; ⬭ Oval hollow; □ Quadratic hollow; Y Y-shape

Ribs; Helical wrap; Sand coat; Helical wrap + sand coat; N/A Currently unknown

Table 6—Manufacturer specifications for # 3 GFRP rebars

Manufacturer		Unit Weight		Area		Load Capacity		Max. Stress		Elastic Modulus		Strain
ID†	Type	$\frac{kg}{m}$	$\frac{lbs.}{ft}$	mm²	in.²	kN	kip	MPa	ksi	GPa	10^6 psi	%
AFR		0.149	0.100	72.3	0.112	59.0	13.25	821.0	119.1	46.0	6.67	1.81
ASL		0.174	0.117	71.0	0.110	58.7	13.20	827.4	120.0	44.8	6.50	1.79
ATP		0.190	0.128	71.0	0.110	91.0	20.46	958.0	139.0	47.0	6.82	2.03
BBM		0.150	0.101	71.0	0.110	71.0	15.96	1000.0	145.0	72.0	10.44	1.50
BPC	TUF 40GPa	0.149	0.100	71.0	0.111	69.8	15.70	983.8	142.7	49.1	7.12	2.30
BPC	TUF 60GPa	0.193	0.130	93.0	0.144	86.1	19.36	1370.5	198.8	63.7	9.24	2.20
KOD		0.159	0.107	86.0	0.121			800.0	116.0	40.8	5.92	
MAR		0.149	0.100	80.0	0.124	95.0	21.36	855.6	124.1	52.0	7.54	1.78
PAL	Sandard	0.182	0.122	81.3	0.126			1100.0	159.0	52.5	7.61	2.10
PAL	Low Modulus	0.135	0.091	47.1	0.073			880.0	128.0	42.5	6.16	2.07
PAL	High Modulus	0.243	0.163	105.8	0.164			1372.0	199.0	65.1	9.44	2.11
PUN		0.233	0.157	95.0	0.147	103.0	23.16	1085.0	157.4	63.2	9.17	1.86
SIR		0.150	0.101	71.0	0.110	75.0	16.86	1000.0	145.0	46.0	6.67	2.00

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Fibre Reinforced Polymer (FRP) Rebar- Current Status

Table 1—North American guidelines for FRP reinforcement bars

Design Guidelines	Title	Main Focus
Association of State Highway and Transportation Officials (AASHTO)		
GFRP-1	AASHTO LRFD Bridge Design Guide Specifications for GFRP- Reinforced Concrete Bridge Decks and Traffic Railings	Structural
Florida Department of Transportation (FDOT)		
DEV932	Nonmetallic Accessory Materials for Concrete Pavement and Concrete Structures	Material
American Concrete Institute (ACI)		
440.1R-15	Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars	Structural
440.3R-12	Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures	Material
440.5-08	Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars	Structural
440.6-08	Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement	Material
440.9R-15	Guide to Accelerated Conditioning Protocols for Durability Assessment of Internal and External Fiber-Reinforcement	Material
Canadian Standards Association (CSA)		
CAN/CSA-S06-15	Fiber Reinforced Structures, Canadian Highway Bridge Design Code (Pages 693-728)	Structural
CAN/CSA-CSA-S806-12	Design and Construction of Building Components with Fiber-Reinforced Polymers	Structural
CAN/CSA-S807-10	Specification for Fiber-Reinforced Polymers	Material
Design Manual No. 3	Reinforcing Concrete Structures with Fiber Reinforced Polymers	Structural
Design Manual No. 4	FRP Rehabilitation of Reinforced Concrete Structures	Structural
Design Manual No. 5	Prestressing Concrete Structures with FRPs	Structural

Table 2—International guidelines for FRP reinforcement bars

Design Guidelines	Title	Main Focus	Applicability
International Organization for Standardization (ISO)			
14484:2013 ED1	Performance guidelines for design of concrete structures using fiber reinforced polymer(FRP) materials	Structural	International
25762	Guidance on the assessment of the fire characteristics and fire performance of fibre-reinforced polymer composites	Structural	International
10406-1	Fibre-reinforced polymer (FRP) reinforcement of concrete - Test methods - Part 1: FRP bars and grids	Material	International
International Code Council (ICC)			
AC454	International Code Council, Evaluation Service, Acceptance Criteria for Fiber Reinforced Polymner (FRP) bars for Internal Reinforcmenet of concrete members, June 2016	Material	International
International Federation for Structural Concrete (FIB — Fédération Internationale du Béton)			
Bulletin #10, Sec-7	Bond of reinforcement in concrete; Bond of non-metallic reinforcement	Structural	Europe
Bulletin #40	FRP reinforcement in RC structures	Structural	Europe
Institute of Structural Engineers (ISE)			
	Interim Guidance on the Design of Reinforced Concrete Structures Using Fiber Composite Reinforcement	Structural	United Kingdom
The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF)			
22-A 98741	Eurocrete Modifications to NS3473 When Using FRP Reinforcement	Structural	Norway
National Research Council (CNR — Consiglio Nazionalle delle Ricerche)			
DT 203/2006	Guide for the Design and Construction of Concrete Structures Reinforced with Fiber-Reinforced Polymer Bars	Structural	Italy
Ukrainian State Standards (DSTU)			
NBV 2.6-185-2012	Guidelines for the design and manufacture of concrete structures with non-metallic composite reinforcement on the basis of basalt and glass fiber rovings	Structural	Ukraine
Standards of the Republic of Belarus (STB)			
1103-98	Glass-fiber plastic reinforcement. Technical requirements	Structural	Republic of Belarus
Egyptian Code of Practice (ECP)			
208-2005	Egyptian code of practice for the use of fiber reinforced polymer (FRP) in the construction fields Egyptian standing code committee for the use of fiber reinforced polymer (FRP) in the construction fields, 2005	Structural	Arab Republic of Egypt
Standardization Administration of China (SAC)			
GB/T 1446-2005	Fiber-reinforced plastics composites-The generals for determination of properties	Material	China
GB/T 1447-2005	Fiber-reinforced plastics composites-Determination of tensile properties	Material	China
GB/T 50608-2010	Technical code for infrastructure application of FRP composites	Structural	China
GB/T 26743-2011	Fiber reinforced composite bars for civil engineering	Material	China
GB/T 29552-2013	Fiber reinforced plastics composites bridge decks	Structural	China
50367-2013	Code for design of strengthening concrete structures	Structural	China
Japan Society of Civil Engineers (JSCE)			
NO. 30	Recommendation for design and construction of concrete structures using continuous fiber reinforcing materials (Design)	Structural	Japan & China

DNVGL-ST-C502
Offshore concrete structures

Annex R on Embedded FRP Reinforcement to EN 1992 (Eurocode 2)

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Japan Society of Civil Engineers (JSCE)			
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	ACI 440.11	CSA S 806	EC 2 Annex R
Glass FRP	Covered	Covered	Covered
Basalt FRP		Covered	
Aramid FRP		Covered	
Carbon FRP		Covered	Covered
Solid Round Bars	Covered	Covered	Covered
Solid Square Bars		Covered	Covered
Grids		Covered	Covered

DNVGL-ST-C502
Offshore concrete structures

Annex R on Embedded FRP Reinforcement to EN 1992 (Eurocode 2)

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Fibre Reinforced Polymer (FRP) Rebar- Current Status

1- Highways and Roads

- Barrier walls • Sidewalks • Bridge decks • Garages • post-tensioned structural members

2- Infrastructure Marine Environments

- Quays • Caissons • Jetties • Piers • Underwater tunnels • Piles • Drilling rig • Port fittings

3- Corrosive Environments

- Tanks and reservoirs of petrochemical products • Pulp and paper industry • Water and wastewater applications

4- On-Grade and Underground Structures

- Slabs and raft foundations • Retaining walls • Tunnel lining • Mine corridors

5- Structures in need of Electromagnetic Neutrality

- Hospitals
- Airports
- Maglev railways

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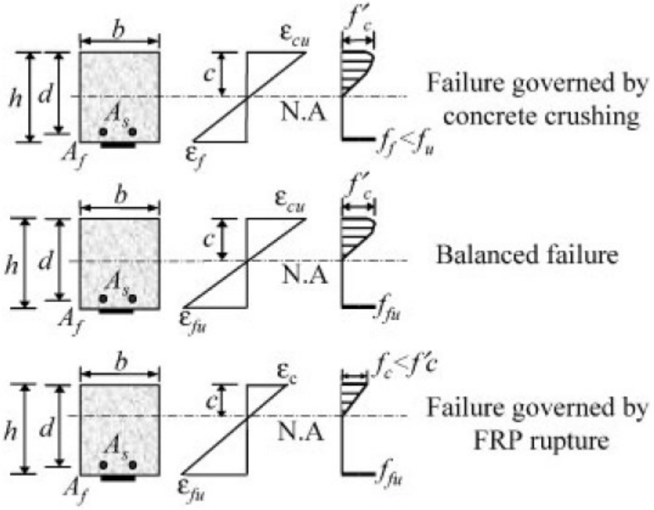
Discussion on Key Concerns Related to the Use of GFRP Rebar

Brittle failure



In many instances, serviceability criteria, creep rupture endurance limits may control the design

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Brittle failure

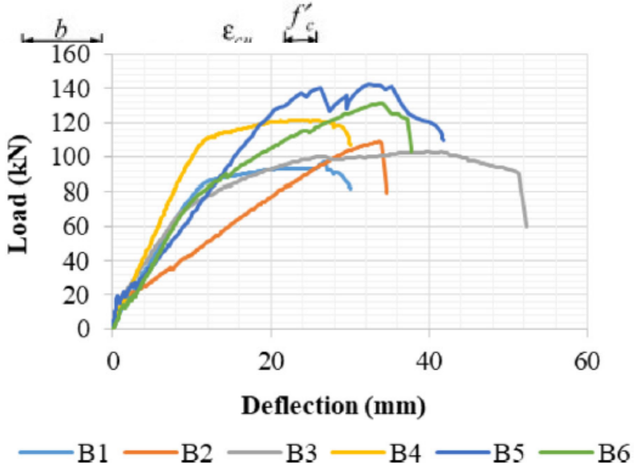


Fig. 8 Load-vertical deflection relationships of all tested beams

In many instances, serviceability criteria, creep rupture endurance limits may control the design

Discussion on Key Concerns Related to the Use of GFRP Rebar

Concrete Cracking

a: Crack Patterns at Failure load 9.80 ton for Tested Beam (B1)

Steel reinforced concrete

b: Crack Patterns at Failure load 33.90 ton for Tested Beam (B2)

GFRP reinforced concrete

Moawad and Fawzi *Journal of Engineering and Applied Science*
https://doi.org/10.1186/s44147-021-00028-6

Discussion on Key Concerns Related to the Use of GFRP Rebar

Concrete Cracking

With GFRP

With Steel

A study comparing steel and GFRP re-bar options for road pavements- West Virginia Department of Transportation

https://www.fhwa.dot.gov/publications/publicroads/08sep/01.cfm

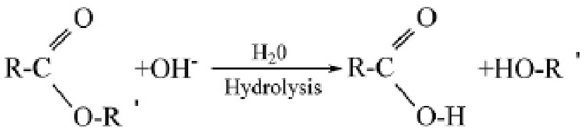
Experimental Results at 7, 28, and 38 Days, and 4 Months

Test	Steel-Reinforced CRCP	GFRP-Reinforced CRCP
Average Compressive Strength at 7 Days (tested at WVU)	19.7 MPa (2,850 psi)	19.7 MPa (2,850 psi)
Average Compressive Strength at 28 Days (tested at WVU)	26.9 MPa (3,900 psi)	26.9 MPa (3,900 psi)
Average Compressive Strength at 4 Months (tested at WVDOT and WVU)	37.6 MPa (5,450 psi)	37.9 MPa (5,500 psi)
Midsection Cracks at 3 Days	45	19
Midsection Cracks at 38 Days	75	40
Midsection Average Crack Spacing at 3 Days	2.88 meters (9.44 feet)	6.91 meters (22.67 feet)
Midsection Average Crack Spacing at 38 Days	1.71 meters (5.61 feet)	3.31 meters (10.86 feet)
Midsection Average Crack Width at 3 Days	0.025 centimeter (0.01 inch)	0.043 centimeter (0.017 inch)
Midsection Average Crack Width at 38 Days	0.028 centimeter (0.011 inch)	0.053 centimeter (0.021 inch)
Maximum Crack Width on January 31, 2008	0.058 centimeter (0.023 inch)	0.086 centimeter (0.034 inch)

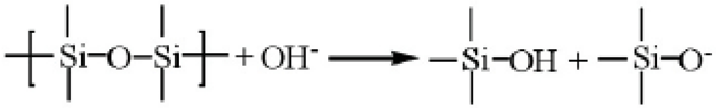
Discussion on Key Concerns Related to the Use of GFRP Rebar

Durability

FRP bars provide significantly higher durability than steel reinforcement bars (deterioration rate can be 100 times slower than steel bars).



Resin degradation



Fibre degradation

Discussion on Key Concerns Related to the Use of GFRP Rebar

Durability

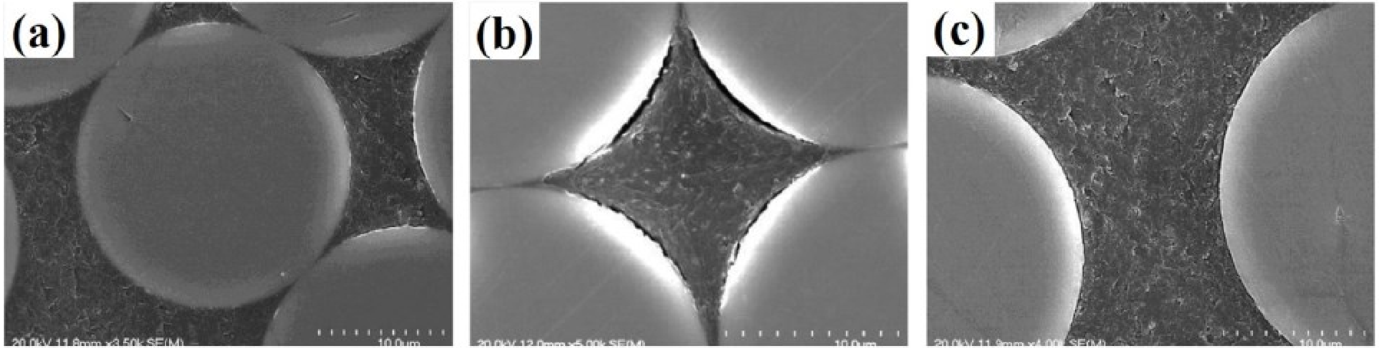


Fig. 6. Fiber-resin interfaces of GFRP bar after soaking in an alkaline solution [51]: (a) epoxy resin, (b) polyester resin, and (c) vinyl ester resin.

https://doi.org/10.1016/j.cemconcomp.2022.104758

Discussion on Key Concerns Related to the Use of GFRP Rebar

Durability

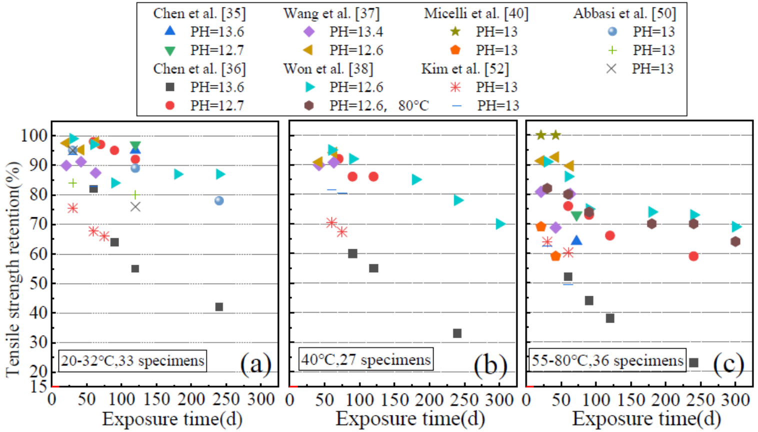


Fig. 3. Variation in tensile strength rate of GFRP bars with corrosion age under varying alkalinities: (a) 20–32 °C, (b) 40 °C, and (c) 55–80 °C.

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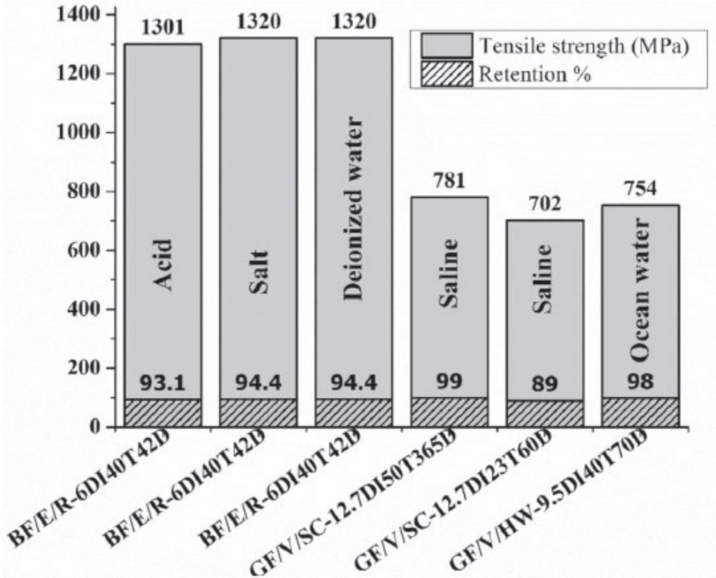

https://doi.org/10.1016/j.conbuildmat.2020.119484

Discussion on Key Concerns Related to the Use of GFRP Rebar

Durability- use with Sea Water and Sea Sand Concrete

Presence of sea water improves the durability in comparison to tap water

Compositions of simulated SWSSC pore solutions [60]

Solution type	Chemicals	Concentration (g/L)	pH value
N-SWSSC solution	NaOH	2.4	13.4
	KOH	19.6	
	Ca $(OH)_2$	2	
	NaCl	35	
HP-SWSSC solution	NaOH	0.6	12.7
	KOH	1.4	
	Ca $(OH)_2$	0.037	
	NaCl	35	

*N-SWSSC – normal seawater sea sand concrete
*HP-SWSSC- high-performance seawater sea sand concrete

Effect of conditioning on the tensile strength of the conditioned FRP bars.

FRP type	Bar diameter (mm) and sizing shape	Environmental exposure			Tensile strength (MPa)	Retention %	Ref.
		Solution	Temperature(°C)	Time (days)			
GFRP/V	9.53, helically wrapped	Ocean water	40	70	754	98	[50]
GFRP/V	9.53, helically wrapped	Alkaline	60	60	482	52	[50]
BFRP/E	6, ribbed	HP-SWSSC	32	21	1341	99.3	[60]
BFRP/E	6, ribbed	N-SWSSC	55	63	352	26	[60]
GFRP/E	6, helically wrapped	HP-SWSSC	32	63	1036	97.9	[60]
GFRP/E	6, helically wrapped	N-SWSSC	55	42	728	68.7	[60]

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Discussion on Key Concerns Related to the Use of GFRP Rebar

Costs

Rebar- Straight bar	Cost CAD/1m of 10 mm	Cost CAD/1m of 15 mm
Black steel	0.706	2.017
Epoxy	0.982	2.8
Galvanized steel	1.256 or 1.69	3.58 or 4.85
GFRP	1.413	2.5 to 4
Stainless steel	2.75	7.85

Provided by **CMTE Inc.**

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Summary

- GFRP rebars provide a much durable reinforcement solution than steel reinforcement
- GFRP rebar technology is well established around the world
- Many design standards for design of reinforced concrete structures also include GFRP rebar solutions
- Choice of resin significantly affects the long-term durability- epoxy and vinyl resins are more favoured than polyester resins
- Potential to use GFRP rebar with seawater and sea sand concrete could be an added advantage
- Manufacture and certify within Scotland- an excellent opportunity for offshore wind projects

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Thank You!!!

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