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Review

Recyclable thermoplastic FRP bars for reinforced concrete structures: Current status and future opportunities

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A B S T R A C T

Replacing steel reinforcing bars in reinforcing concrete (RC) structures with fibre-reinforced polymer (FRP) bars is an effective approach to avoid problems associated with corrosion of steel bars due to external chloride ions and humid environments. Recently, thermoplastic FRP bar has attracted much attention due to its advantages such as recyclability and on-site workability. In particular, bendable FRP threaded bars made of thermoplastic composites are very easy to be processed on-site due to their flexibility when heated. A number of studies have been conducted on recyclable thermoplastic FRP bars for reinforced concrete structures. This article provides a comprehensive overview of the benefits associated with thermoplastic FRP bars. The basic properties of thermoplastic FRP bars (including mechanical properties, durability properties and creep properties, etc.) are reviewed and summarized, and the comparisons between them and thermosetting FRP bars are conducted. Opportunities for further research on thermoplastic FRP bars in terms of material properties and structural engineering applications are finally identified.

1. Introduction

Fiber-reinforced polymer (FRP) bars are a high-performance composite material made by embedding continuous fibers in a resin matrix. They can effectively replace traditional steel bars for reinforcing concrete members under specific working conditions. In recent years, FRP bars have been increasingly used in civil engineering due to their advantages (such as excellent corrosion resistance, high specific strength, easy cutting, non-magnetic properties, etc.) [1–8]. Currently, thermosetting FRP bars are the most widely used, which are usually made of continuous fibers such as glass fiber, carbon fiber, aramid fiber or basalt fibers and thermosetting resin such as vinyl ester resin or epoxy resin through pultrusion molding process [9–16]. The fiber volume ratio is usually between 55 % and 70 %. Thermosetting resin is generally a cross-linked polymer that is formed by cross-linking curing and solidification under certain conditions, and thermosetting resin generally does not re-melt or soften again after heating [17,18]. Thermosetting resin is non-biodegradable and it can stay in the natural environment for hundreds of years, which impacts the environment extensively [19,20]. Therefore, the disposal of FRP bar waste (including other thermosetting FRP products) containing thermosetting resin is becoming an environmental problem that needs to be solved urgently [21–23].

The waste of thermosetting FRP bars primarily originates from two aspects. Firstly, the waste generated after the end of the service life of structures reinforced with thermosetting FRP bars and would continuously accumulate over time [24,25]. Secondly, during the production process of thermosetting FRP bars, the difficulty in manufacturing complex shapes due to the use of thermosetting resin leads to the accumulation of waste. This process not only inevitably generates a large amount of waste during production but also hinders the recycling and utilization of the waste [26]. Additionally, FRP bars are widely used as the anchorage nail for foundation pits, as their characteristics allow them to be crushed by shield tunneling machines without damaging the equipment. Consequently, they are left in the soil outside the construction pit, contributing to the generation of waste [27–29]. Unlike many other common materials (especially metals, wood, and concrete), the recycling and reuse of waste from thermosetting FRP bars are more challenging and expensive [30–34]. The waste of thermosetting FRP bars is typically managed through three methods: landfill, incineration, and mechanical recycling [35]. Currently, landfill is the most common

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method. The cost of landfill is expected to rise, leading to an overall increase in expenses and rendering it unsustainable in the future [36,37]. Given the costs, environmental concerns, and regulatory restrictions associated with landfilling and incineration of FRP bar waste, there is an increasing focus on recycling FRP bar waste in concrete. However, previous studies indicate that substituting FRP bar waste for aggregates significantly reduces the strength of concrete [38–42]. Therefore, the feasibility of using mechanically recycled FRP bar waste in concrete or mortar remains uncertain [26].

In recent years, with advancements in production technology and an increasing demand for recyclability and sustainability, manufacturers of reinforcing bars have introduced FRP bars made from thermoplastic resins, which have been successfully applied in engineering projects. Such projects include the La Chancelière Bridge that utilized thermoplastic FRP rebar for reinforcement and a bulkhead in New York reconstructed using thermoplastic FRP rebar to enhance its durability. Due to the characteristics of thermoplastic resins, such as re-meltability and enhanced toughness, they are able to later-stage re-shape, recycle, and reuse [43]. The use of thermoplastic resins enables more effective recycling and re-processing of FRP bars at the end of their structural lifespan and of waste generated during the production process, leading to reduced processing costs, and diminished environmental impact [44–46]. Consequently, in comparison to traditional thermosetting FRP bars, thermoplastic FRP bars are more environmentally friendly and align better with sustainability requirements.

On the other hand, while steel rolling mills allow shaping and cutting rebars based on orders for usage at construction sites [47], thermosetting FRP rebars cannot be reshaped and the lack the capability for secondary processing at construction sites due to the cross-linked polymer structure formed by the curing of thermosetting resin. The bending and shaping of FRP stirrups and ties must take place at the manufacturer's facility, and more importantly lead to degradation in strength of the FRP bars [48,49] (Fig. 1). Moreover, construction drawings for the reinforcing bars must be confirmed well in advance, with often lengthy delivery periods from the manufacturers. Orders must be placed well in advance to lock in delivery dates, and any mid-course changes to the bending drawings would incur significant cost implications. Thermosetting resin-based polymers are used traditionally for FRP but have poor recyclability. In contrast, thermoplastic based polymers (such as polypropylene) can be processed without an autoclave and are melt recyclable.

The use of thermoplastic resin allows to produce coiled FRP bars or stocked straight FRP bars, which can be heated and softened on-site, then bent into the desired shape and cooled. This flexibility at the construction site can improve efficiency and reduce material waste, as detailed in the literature [50,51]. More importantly, FRP bars with thermoplastic resin also enable more desirable performance such as better fracture toughness and heat resistance. Besides, thermoplastic FRP bars offer a high strength-to-weight ratio, making them easier and more cost-effective to transport, handle, and install, while also reducing the overall weight load on structures. Thermoplastic FRP composites are inherently resistant to corrosion, significantly enhancing the durability and longevity of structures [52,53].

The above content highlights thermoplastic FRP bars are becoming increasingly popular in civil engineering and are more aligned with the principles of sustainable development. However, they also have some drawbacks such as higher initial costs, difficulty in fabrication, limited long-term data, the need for specialized design and installation practices, bonding issues with concrete, and lower stiffness. Balancing these pros and cons is essential to ensure their effective use in various structural applications. Although current studies on thermoplastic FRP bars in construction have led to profound knowledge, it is necessary to identify research gaps in this field to promote the application of thermoplastic FRP bars. Specifically, further research is needed to obtain comprehensive long-term performance data, improve bonding techniques with concrete, and optimize manufacturing processes to reduce initial costs. Additionally, developing standardized design and installation guidelines and investigating the environmental impacts of large-scale production and recycling of thermoplastic FRP bars are crucial to fully leverage their benefits in sustainable construction. To this end, this paper primarily selects recent relevant literature to provide a comprehensive review of the basic characteristics of thermoplastic FRP bars, including the properties of the constituent materials, basic mechanical performance, bonding performance, and durability. It mainly describes further research opportunities for the material characteristics and structural applications of thermoplastic FRP bars, while also reviewing the current research deficiencies and directions that require further in-depth study in the future.

2. Thermoplastic FRP Rebar: Composition and basic properties

Like traditional FRP composite materials, thermoplastic FRP bars are also manufactured by embedding continuous fibers (such as glass fibers, carbon fibers, or basalt fibers) in the resin matrix. Fibers are the main components that bear external loads, with the resin transmitting stress to and between fibers and protecting them from environmental corrosion [1,54–57]. The characteristics of thermoplastic FRP bars depend on the properties of the reinforcing fibers, the type of polymer matrix, fiber orientation, fiber content, and the bonding performance between fibers and the matrix. Fig. 2 summarizes various fiber-reinforced composite materials used in the field of civil engineering.

2.1. Components of thermoplastic FRP bars

2.1.1. Fiber

Fibers are the most critical components controlling the physical and

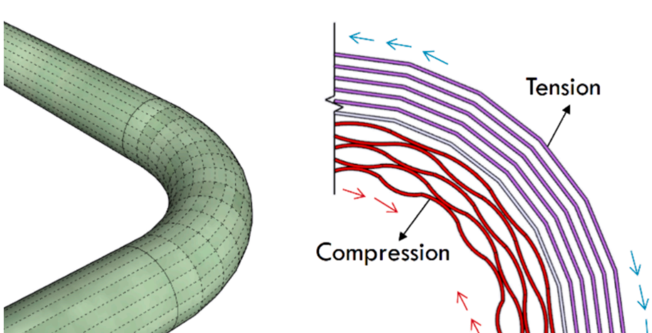


Fig. 1. Fiber squash and stretch in FRP bar reinforcement based on pultrusion.

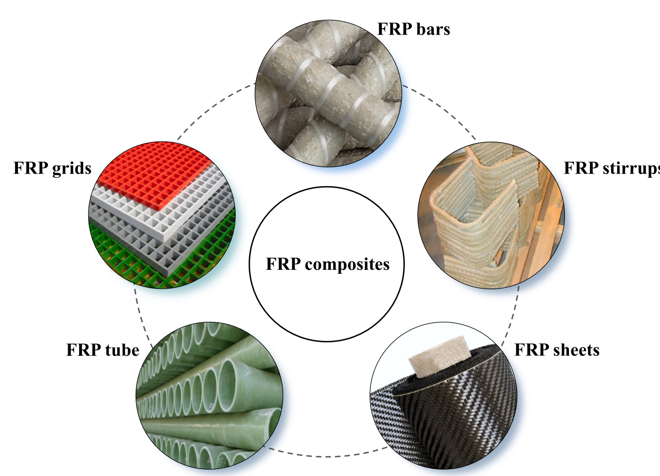


Fig. 2. FRP composites used in construction.

mechanical properties of thermoplastic FRP bars. Commonly used fibers in civil engineering construction include carbon fibers, glass fibers, aramid fibers, and basalt fibers. These fibers, when combined with a resin matrix, form composite materials known as CFRP (carbon FRP), GFRP (glass FRP), AFRP (aramid FRP), and BFRP (basalt FRP) [58–62]. Fig. 3 illustrates a performance comparison between different types of FRP and steel. To provide a comprehensive understanding of thermoplastic FRP bars, Table 1 presents the typical material properties of commonly used fibers in civil engineering.

Different fibers possess their unique characteristics. The main characteristics of glass fibers are high strength, water and chemical resistance, and very importantly low cost, which is why glass fibers are most used in the construction industry. However, the main disadvantages of glass fibers are relatively low modulus of elasticity, relatively poor alkali resistance, and poor creep resistance [59,66,67]. Carbon fibers possess advantages include high strength, high modulus of elasticity, good creep resistance, low density, resistance to chemical influences, low electrical conductivity and non-absorption of water. The production of carbon fibers is at higher costs, which is also considered a weakness of the carbon fibers [59,66]. Basalt fiber made from a type of igneous rock by rapid cooling of lava. This fiber has a high tensile strength, perfect resistance to high temperatures and good durability [68–70]. Aramid fibers are characterized by low density, high tensile strength, high modulus of elasticity and high stiffness. These fibers can be used in static and impact resistant structures. However, their application is limited by their low long-term strength (stress fracture) and radial strength. In addition, difficulty in cutting and processing is another weakness of aramid fibers [59,66].

2.1.2. Matrix

While the mechanical properties of thermoplastic FRP bars, such as the elastic modulus and strength, are primarily determined by the fibers, the resin matrix also plays a crucial role. The resin matrix serves as a bridge between the fibers, bringing the fibers together in resisting loads, preventing fibers from easily buckling under compression. This ensures that thermoplastic FRP bars exhibit satisfactory shear and longitudinal load resistance, securing effective synergy among the fibers within the bars [71–77]. In addition to the matrix resin, some special components (such as curing agents, fillers, and other additives) may be added to improve the processing properties of the material and the performance of the FRP products, or to reduce the raw lower production costs [34].

In general, resins can be categorized into two types: thermosetting resins and thermoplastic resins. Thermosetting resins are incapable to be further processed by bending or welding due to the formation of irreversible chemical cross-linking structures after curing. However, they have advantages such as higher strength, lower viscosity, easier

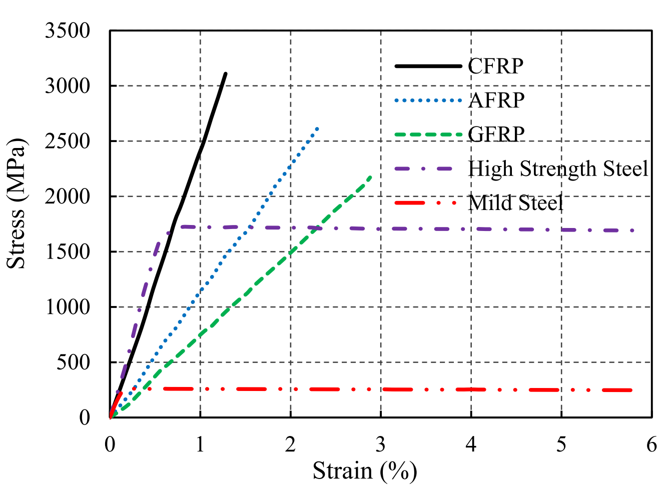


Fig. 3. Comparison of properties between different types of FRP and steel.

processing in fabrication, and higher production efficiency [78]. Therefore, thermosetting resins are currently the main-stream matrix for FRP composites. The pultrusion process is a common manufacturing technique in the production of FRP composites. This process is characterized by its high production efficiency [79–81], low cost [82,83], and the ability to produce products with stable performance. Additionally, it has the advantage of being able to produce reinforcing materials of almost unlimited length [84].

Luisier et al. [85] proposed the categorization of thermoplastic extrusion processes, which can be divided into two types: non-reactive pultrusion and reactive extrusion (Fig. 4). The non-reactive thermoplastic extrusion process involves mechanical components such as a fiber tow spindle, creel, guiding system, resin trough, heaters and molds, conveyor belt, and mechanical cutting saw [86–89], as shown in Fig. 5. The reactive extrusion process is developed given that the extrusion process is combined with reaction injection molding (RIM). A RIM resin impregnation device is shown in Fig. 6 [90]. In the reactive extrusion process, preheated, unimpregnated fibers are fed into the heating module, where they are impregnated, and the matrix undergoes in-situ polymerization. The resulting polymerized matrix exhibits the characteristics of a thermoplastic melt [91]. The main difference between reactive extrusion and non-reactive extrusion processes lies in the design of the heating module. In the reactive extrusion process, the viscosity of the thermoplastic resin solution is lower compared to thermoplastic polymers in the non-reactive extrusion process. This lower viscosity can enhance and expedite impregnation, thereby increasing productivity [92–94].

There is a trend of replacing thermosetting resin matrices with thermoplastic resin matrices has become popular. Generally, the molecular chains of thermoplastic matrices are linear or branched, and there are no chemical bonds formed between the molecular chains [95]. They can be recycled through reversible physical changes, such as melting with heat and cooling for shaping, with minimal impact on mechanical performance and microstructure in processes like pultrusion [96]. The thermoplastic matrix has a high viscosity and a low strength, making it challenging to work with fibers when considering stress transfer between fibers and resin. When reducing the viscosity of the thermoplastic resin and strengthening the bonding at the fiber-resin interface, the thermoplastic resin matrix becomes more suitable for complex working environments. Common thermoplastic resins include polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyamide (PA), polycarbonate (PC), and polyetheretherketone (PEEK), as shown in Table 2. Among these, PP with advantages such as abundant raw material source, low cost, ease of processing and shaping, and good mechanical and heat-resistant properties, has become the fastest-growing synthetic matrix and can meet the production needs of FRP.

In complex environments characterized by factors such as temperature, humidity, corrosive conditions, and dynamic/static loads, the long-term use of FRP composite materials can lead to the degradation of mechanical performance. Therefore, it is necessary to gain an in-depth understanding of the mechanical properties, durability, and creep behavior of thermoplastic FRP bars [97].

3. Mechanical properties of thermoplastic FRP bars

3.1. Basic mechanical properties

Mechanical properties of thermoplastic FRP bars, including tensile performance, transverse shear strength, and interlaminar shear strength are of significance. The tensile performance of FRP is one of the most crucial parameters influencing the design of structures with FRP reinforcement. Tensile performance determines the load-bearing capacity of the section, while the tensile modulus determines the ultimate limit state. The primary factors affecting the tensile performance of FRP bars are the type of fibers and the fiber volume fraction [98], while studies

Table 1
Physical and mechanical properties of commonly used fibers [63–65].

Properties	Electrical-resistant E-glass	High-strength S-glass	Alkali-resistant AR-glass	Carbon	Basalt	Aramid
Density (kg/m^3)	2500	2500	2270	1700	2800	1440
Filament diameter (μm)	6–21	6–21	6–21	5–15	6–21	5–15
Tensile strength (MPa)	3450	4580	1800–3500	3700	3000–4840	2900–3450
Deformation modulus (GPa)	72.4	85.5	70–76	230–600	93–110	70–170
Elongation (%)	2.4	3.3	2.0–3.0	1.5–2.0	3.1–6	2.8–3.6
Coefficient of thermal expansion (10^{-6}/ °C)	5.0	2.9	n/a	–0.6 up to –0.2	8.0	–2.0 longitudinal 59 radial
Poisson's ratio	0.22	0.22	n/a	0.20	n/a	0.35

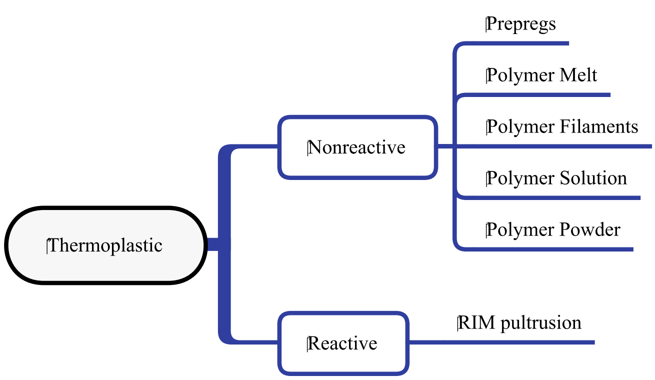


Fig. 4. Thermoplastic pultrusion types.

often overlook the impact of volume fractions on the tensile performance of FRP bars [99]. Tensile strength is also influenced by manufacturing processes, defects, and the properties of thermoplastic resin [100]. The comparisons of mechanical properties of thermoplastic and thermosetting FRP bars are shown in Table 4.

The transverse shear strength represents the maximum strength exhibited by FRP bars when subjected to shear forces, indicating their capacity to withstand shear deformation. It is numerically equal to the tangential stress on the shear plane, i.e., the ratio of the shear force formed on the shear plane to the area of failure. The transverse shear strength of FRP bars mainly comes from both the resin system and fibers as well as fiber-resin interfaces [101]. The interlaminar shear strength refers to the capacity of FRP in resisting interlaminar horizontal stresses which lead to interfacial delamination [102]. The interlaminar shear test has been widely cited and used by researchers as a tool to examine the bond between the fibers and the surrounding resin (fiber/matrix interface).

Extensive studies have been carried out on the basic mechanical properties of thermoplastic FRP bars. Tensile performance of thermoplastic CFRP bars with a diameter of 12.7 mm has been explored by El-Tahan et al. [103]. The experimental results showed that the stress–strain relationship of thermoplastic CFRP bars exhibited linear behavior until failure. The tensile strength of the specimens reached 825 MPa, the elastic modulus was 91 ± 2.6 GPa, and the corresponding maximum strain was 9000 micro-strain. The specific type of thermoplastic resin used in the study was not specified. Rossini et al. [104] investigated the tensile strength of thermoplastic GFRP bars with a diameter of 12 mm made from a non-reactive acrylic resin. The experimental results indicated an average tensile strength of 948 MPa and an average tensile modulus of 48.0 GPa over a measuring area of 116 mm2. Mehrabi et al. [105] reported an experimental study on the tensile performance of a thermoplastic GFRP bar. The results showed that the tensile strength of the 12.7 mm diameter thermoplastic GFRP bar ranged from 827 MPa to 1034 MPa, the elastic modulus ranged from 38 GPa to 52 GPa, and the ultimate tensile strain ranged from 2.0 % to 2.3 %.

Additionally, Benmokrane et al. [51] systematically investigated the physical characteristics and mechanical properties of thermoplastic GFRP bars with three different diameters (10 mm, 15 mm, and 20 mm) made from Elium liquid thermoplastic resin (methyl methacrylate type). Simultaneously, a comparison was made with the thermosetting GFRP bars of 15 mm diameter, as shown in Table 3. The fiber content of thermoplastic bars exceeded the limits of 70 % and 100 °C specified in ASTM D7957 [106] and CSA S807 [107], respectively. The cure ratio of the 15 mm thermosetting bars was 98 %, also surpassing the required 95

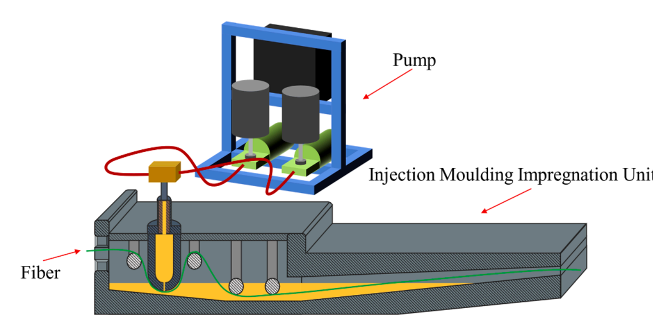


Fig. 6. Reaction Injection Molding (RIM) resin impregnation unit.

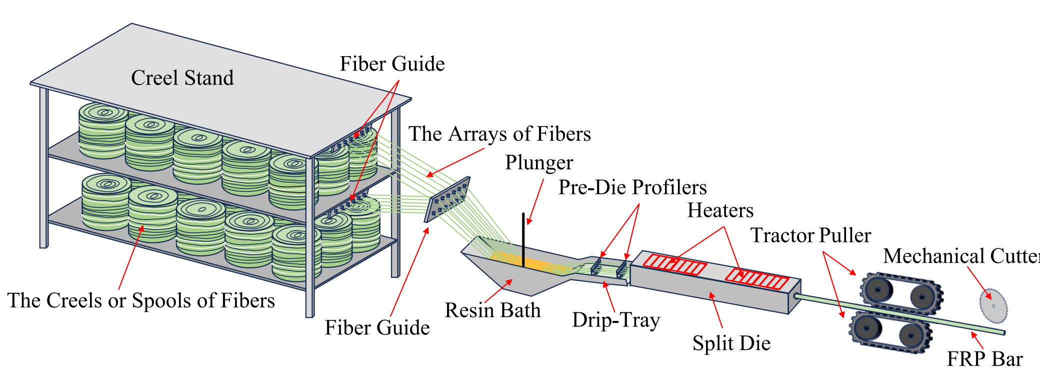


Fig. 5. Non-reactive thermoplastic composite pultrusion process.

Table 2
Material properties of thermoplastic resins (Taylor & Francis Ltd, http://www.tandfonline.com).

Properties	Thermoplastic resins						Thermosetting resins		
	PE	PET	PP	PA	PC	PEEK	Polyesters	Epoxy	Vinyl-ester
Density (g/cm^3)	0.96	1.37	0.91	1.15	n/a	1.32	1.2–1.4	1.2–1.4	1.15–1.35
T_g (°C)	−110	75	−10	n/a	151	143	50–70	105	120–150
T_m (°C)	130	250	170.9	n/a	n/a	334	110–135	90–180	n/a
Tensile strength (MPa)	26	47	28	30–70	59.82	92	34.5–104	55–130	73–81
Tensile modulus (GPa)	1.4	3.1	2	n/a	n/a	3.6	2.1–3.4	2.75–4.10	3.0–3.5
Impact strength	n/a	79 J/m	1.1 J/cm	16–110 J/m	853.1 J/m	83 J/m	n/a	2–21 J/m	n/a
Elongation (%)	n/a	50–300	20	2–56	n/a	2.0	30–80	23–36	5–6

Table 3
Physical properties of thermoplastic and thermosetting GFRP bars [51].

Properties	Thermoplastic resins			Thermosetting resins	Specified Limits for FRP Bars	
	10 mm	15 mm	20 mm	15 mm	ASTM D7957 [106]	CSA S807 [107]
Cross-sectional area (mm^2)	98	246	325	245	*	*
Fiber content by weight (%)	77.6	81.1	77.7	78.5	70	70
Cure ratio (%)	n/a	n/a	n/a	98	95	95
Glass transition temperature, T_g (°C)	103	100	102	106	100	100
Water absorption (%) after 24 h	0.36	0.43	0.58	0.06	0.25	0.25
Water absorption (%) at saturation	0.81	1.08	1.14	0.15	1.0	1.0

* Prescribed limits of cross-sectional area for 10 mm, 15 mm and 20 mm GFRP are 67–104, 186–251 and 268–347 mm^2, respectively.

Table 4
Mechanical properties of thermoplastic and thermosetting GFRP bars [51].

Property	Thermoplastic bars			Thermosetting bars
	10 mm	15 mm	20 mm	15 mm
Tensile strength (MPa)	1421 ± 18.6	1062 ± 27.1	1033 ± 41.8	978 ± 12.1
Tensile modulus (GPa)	65.4 ± 0.3	61.5 ± 1.9	62.5 ± 0.2	59.8 ± 0.7
Tensile strain (%)	2.17 ± 0.03	1.65 ± 0.06	2.14 ± 0.07	1.6 ± 0.01
Transverse shear strength (MPa)	207 ± 0.1	186 ± 6.1	n/a	210 ± 4.2
Interlaminar-shear strength (MPa)	66.6 ± 5.2	46.0 ± 0.3	45.1 ± 0.2	62.6 ± 1.2

% according to ASTM D7957 [106] and CSA S807 [107]. There were significant differences in the moisture absorption of the bars, with the thermosetting bars of 15 mm diameter showing moisture absorption rates of 0.06 % and 0.15 % after 24 h and when saturated, respectively. In contrast, the thermoplastic bars exhibited a higher moisture absorption after 24 h of saturation, not meeting the limits specified in ASTM D7957 [106] and CSA S807 [107]. Additionally, the water absorption rate of the 15 mm thermoplastic bars was seven times that of the thermosetting bars. Micelli and Nanni [108] explained that water diffusion in polymers depends on the degree of crosslinking or crystallinity, respectively, and that the role of temperature in the absorption kinetics of polymer resins is significant.

Table 4 presents the mechanical properties of thermoplastic GFRP bars and thermosetting GFRP bars. Thermoplastic GFRP bars exhibited near-linear elastic behavior under tension before failure, with all specimens suddenly failing due to tensile fiber fracture. The tensile strength was significantly higher than the minimum tensile strength specified in ASTM D7957 [106] and CSA S807 [107] for high modulus GFRP bars.

Furthermore, Benmokrane et al. [51] conducted tensile tests on thermoplastic GFRP bars in elevated temperatures of 40 °C and 70 °C, investigating the influence of high temperatures on the tensile strength of thermoplastic GFRP bars. The results indicated that at 40 °C, the tensile strength and elastic modulus of thermoplastic GFRP bar specimens were unaffected, maintaining 100 % and 98 % of their respective tensile strength and elastic modulus. However, when exposed to a temperature of 70 °C, the strength and modulus of the thermoplastic GFRP bars decreased by 14 % and 4 %, respectively.

D'Antino and Pisani [50] conducted experiments to investigate the tensile and compressive behavior of thermosetting GFRP bars composed of vinyl ester resin and E-glass fibers, as well as thermoplastic GFRP bars composed of reactive acrylic resin and E-glass fibers. The thermosetting bars were designed with three different diameters (10, 12, and 16 mm), while the thermoplastic bars were designed with five diameters (6, 8, 10, 12, and 16 mm). The results indicated that both thermosetting and thermoplastic GFRP bars subjected to tensile tests exhibited similar fiber fracture failure modes, elastic modulus, and tensile strength. For thermosetting bars, the diameter of the bars had a slight impact on tensile strength, while for thermoplastic bars, there was no significant effect. Tensile elastic modulus remained constant as the diameter varied for both thermosetting and thermoplastic bars. In compressive tests, the ratio between compressive strength and tensile strength was higher for thermosetting bars compared to thermoplastic bars, with values of 0.68 and 0.56, respectively.

Basil Ibrahim et al. [109] compared the mechanical performance and strength of the TP bars with that of TS bars of the same size. The test result showed that the TP bars had slightly higher tensile strength and elastic modulus compared with their TS counterparts. The TP bars had 19 % higher tensile strength and 16 % higher elastic modulus than the TS bars. This difference could be attributed to the higher fiber content in the new TP bars, which was 6 % higher than that of the TS bars.

3.2. *Corner strength of thermoplastic FRP bending bars*

Currently, the majority of the non-circular steel bars used in concrete structures are pre-bent and cut in factories according to design specifications, with only a small portion of the bars being bent into specific shapes directly at the construction site. Whether bent on-site or in a factory, traditional steel bars hold significant advantages due to their elastic–plastic behavior. They can be easily shaped through cold bending, offering a cost-effective solution to meet the requirements of most detailed designs [110].

However, secondary-process bending of FRP bars can alter the sectional geometric shape and stress conditions of the fibers at the bending region [111–114]. Under the action of the bending apparatus, the cross-section of the bending region is compressed, causing significant tension in the outer fibers relative to the bending center and significant compression in the inner fibers. This leads to the initiation of defects and stress concentration in the bending region of the FRP bars. When bent unidirectional FRP bars are used as bars in concrete structures, especially when the FRP bars are designed to withstand high tensile stresses, this phenomenon tends to become a very serious problem because premature failure of the bent portion of the FRP bar may occur. In fact, the results of several studies have shown that the tensile strength of the flexural portion of the FRP bar is only 40 % of the maximum tensile strength of the straight portion [111–113,115–118], so the reduction in the strength of the FRP bar needs to be carefully considered when designing the members, as it has a significant impact on the maximum value of strain that can be safely withstood by the load-bearing structure.

Different test methods have been proposed to calculate the strength reduction of bending bars. For example, ACI 440.3R [119] suggests the use of Method B.5 (bending bar capacity) and Method B.12 (corner radius) as shown in Fig. 7(a) and (b). Method B.5 measures the ultimate capacity of FRP bars by testing (stretching) the straight portion of the FRP Type C hoop bar, with the curved end of the bar embedded in two concrete blocks, as shown in Fig. 7(a). The bending capacity of the bent FRP bars was measured and compared with the ultimate tensile strength of the bars to derive a strength reduction factor due to bending effects. Regarding to B.12 Methods, the effect of corner radius on the tensile strength of FRP bars was measured using a test apparatus. The apparatus applies a tensile force in U-shaped FRP that reacts with a bent section mounted on a yoke, as shown in Fig. 7(b).

Wang et al. [120] investigated the tensile strength of a BFRP bar using thermoplastic as the resin matrix after secondary bending, and a BFRP bar with a thermoset epoxy resin as a comparison. To facilitate the process, they developed a specific equipment to heat and bend the thermoplastic FRP bars as shown in Fig. 8. The effects of different bending ratios, diameters, constituent materials and loading methods on the tensile strength of the bent bars were considered. The damage pattern is shown in Fig. 9, and it was indicated that the damage of the bent FRP bars is controlled by the fracture and splitting of the FRP bars in the bent region, and the damage of the bars gradually extends from the bent region to the straight region. The results show that the interlayer shear stresses in the bending region significantly affected the strength retention. The strength of thermoplastic BFRP bending bars was positively correlated with the bending rate and negatively correlated with the diameter of the bending bar, and the strength of thermoplastic BFRP bending bars ranged from 21 % – 39 % of the strength of their straight bars. In contrast, Apitz et al. [121] investigated the tensile strength of thermoplastic CFRP hoops made of semi-crystalline thermoplastic polyamide resins in the bending region. They found that the average strength of thermoplastic hoops reached as high as 71 % of the strength of straight bars. They concluded that the bending capacity of the hoop was influenced by the bond between the concrete and the hoop. The greater the bond stress transferred to the concrete, the smaller the stress reduction in the bending section. That is to say, concrete helps the FRP hoop to mobilize the tension. This explains the bond between the bending and straight regions of the hoop. Additionally, the concrete strength is also an influential parameter. Ehsani et al. [111] found that the bending capacity of the hoop increases as the concrete strength increases.

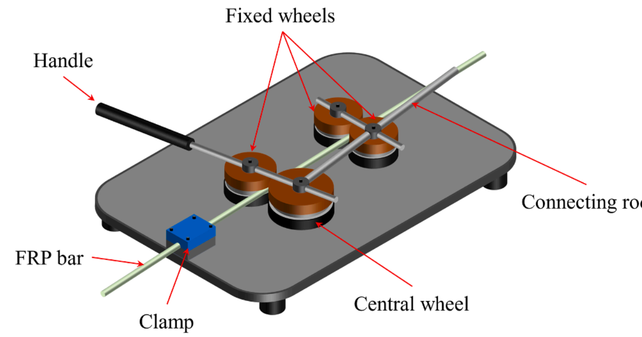


Fig. 8. Bending device for thermoplastic FRP bars [120].

El-Tahan et al. [103] tested four specimens according to the CSA-S806 [122] specification to evaluate the performance and strength of thermoplastic CFRP bending bars used as stirrups. The test variable was the tail length after the bent portion of the bar, while the bending radius was kept constant at four times the bar diameter ($4d_b$). Four specimens with tail lengths of $3d_b$, $6d_b$, $9d_b$ and $12d_b$ using standard hook end anchorage types were tested. It was found that the strength retention in bending was 27 %, 24 %, 37 %, and 24 % for $3d_b$, $6d_b$, $9d_b$, and $12d_b$ tail lengths of bar, respectively. All the specimens were damaged at the bent region of the bar except for the $12d_b$ specimen which was damaged by early splitting. The specific type of thermoplastic resin used was unknown. Currier et al. [114] conducted an experimental study on two types of thermoplastic FRP bars, aramid fiber reinforced nylon and carbon fiber reinforced nylon, with a fiber volume content of 50 % and a rectangular cross-section of 2.4 mm × 7.1 mm. Appendix B.5 recommended by ACI.440.3R-04 [119] was used to test the strength of FRP bending part, and the results showed that the tensile strength of FRP bending part was only 23 % of that of straight bar, and the damage at the bending part was mainly caused by stress concentration.

3.3. Macro-mechanical modeling of the strength of FRP bars in bent areas

Imjai and Pilakoutas [123,124] proposed a theoretical model that applies macromechanics to analyze and predict the strength of FRP

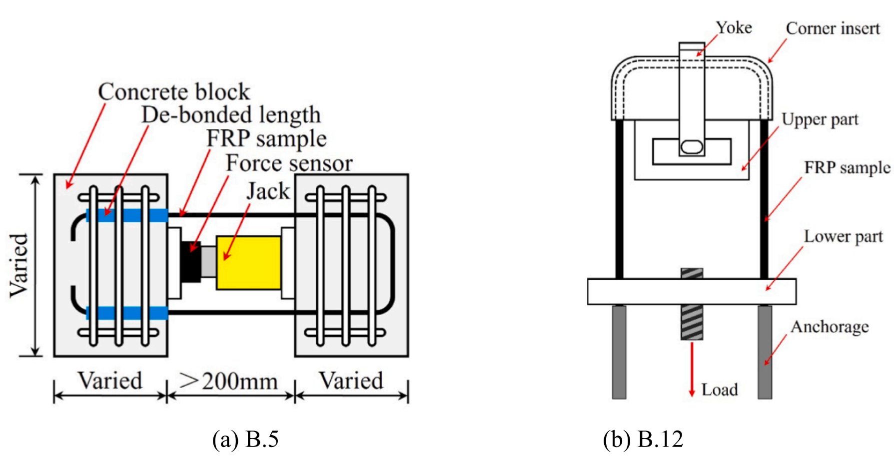


Fig. 7. ACI test methods for bent FRP bars.


Fig. 9. Typical failure modes in the bending region [120].

bending bars in the bending region. When the FRP bent bar is embedded in a concrete structure, the distribution of transverse stresses on the inside of the FRP bent bar is primarily related to the bond characteristics of the concrete and the FRP bar, and the surface geometric parameters of the FRP bar. This study involves the unidirectional composite bars with a rectangular cross-section as an example, ignoring the bond stress between the bent part of the FRP bar and the concrete, assuming that the bent part is a quarter circle with an inner diameter of r. Due to the transverse compression of the concrete and the tensile effect along the axial direction (fiber direction), with the shear effect at the interface being ignored, the stress state of the bent part is a plane stress state, which can be expressed in Fig. 10.

3.4. Effect of FRP bar cross-section deformation on the strength of the bending area

In order to make full use of thermoplastic FRP bar that can be reprocessed and thus improve the flexibility and convenience of on-site construction, the resin can be softened by heating, the bar can be confined by bending molds when bending, and then it can be cooled, shaped and demolded after bending. However, when the thermoplastic FRP bar is preheated and bent, the cross-section shape of the bent part of the bar will be changed, and the cross-section will be flexed and flattened to a certain extent, and for a round cross-section, this deformation is more obvious. Due to the relatively limited plasticity of the fiber, the size of the cross-section deformation has a great influence on the mechanical properties of thermoplastic FRP bent bars, it is necessary to investigate the effect of cross-section deformation on strength, as shown in Fig. 11 [123].

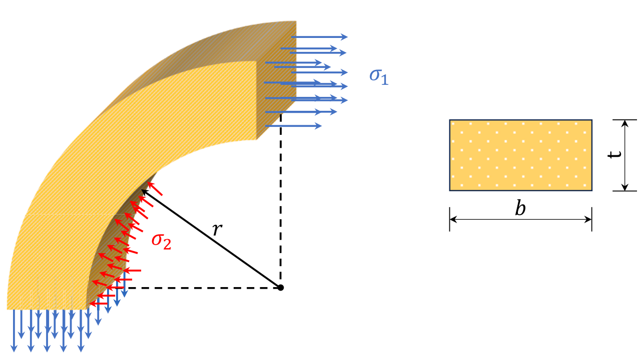


Fig. 10. Stress distribution in the bending part of FRP bending bars in concrete [123].

3.5. Creep properties of thermoplastic FRP bars

The performance of FRP bars under sustained loading is a function of the interaction between the interface of the two materials, fiber and resin. In addition to the choice of material, the sizing and surface treatment of the fibers play an important role in ensuring mechanical bonding between the fibers and the resin. The surface treatment of the fibers also affects their protection against corrosive chemicals.

Sayed-Ahmed et al. [102] conducted two-stage creep tests on thermoplastic GFRP bar with a diameter of 10 mm at 20 % and 40 % ultimate tensile strength (UTS) for 816 h. The results showed that the tensile strains increased by 8.00 % to 10.26 % from the initial strains after being loaded by the 20 % UTS for 816 h, while the tensile strains increased in the range of 6.35 % to 10.59 % for the specimens loaded by the 40 % UTS. The tensile strains of the specimens loaded with 40 % UTS increased in the range of 6.35 % to 10.59 %. The average tensile strength exceeded 1000 MPa, the tensile modulus was 62.5 GPa, and the creep strain was insignificant with 90 % strength retention and 100 % modulus retention during the test period. Benmokrane et al. [51] tested six thermoplastic GFRP bars with a diameter of 10 mm for more than 417 days (10,000 h) to investigate their creep behavior. A comparison was also made with thermoset GFRP bars under the same conditions. The test results show that after 10,000 h of continuous tensile loading, the creep strain of a 10 mm thermoplastic GFRP bar at a high stress of 40 % UTS is about 8 % of the initial value. The long-term creep strain of thermoplastic GFRP bar obtained from the study was essentially the same as the long-term creep strain characteristics of thermoset GFRP bar.

4. Bonding properties of thermoplastic FRP bar to concrete

The bond performance between FRP bars and concrete primarily depends on the material characteristics of the FRP bars, bonding length, concrete strength, surface treatment of the FRP bars, and dimensional properties. Currently, there have been numerous experimental studies on the bond performance between FRP bars and concrete, addressing various influencing factors. However, these studies are mainly focused on thermosetting FRP bars, and research on the bond performance between concrete and FRP bars with a thermoplastic resin as the matrix material is limited. The experimental methods for studying the bond performance between FRP bars and concrete can be categorized into three types based on the testing objectives: the first type is the uniaxial pullout test, which is primarily used to determine the bond strength between FRP bars and concrete and to compare the bonding anchorage performance of various types of FRP bars; the second type is the beam test or simulated beam test, which is conducted to ascertain the applicable design strength of bonding anchorage and related structural requirements; The third type is the local bond slip test, which is mainly

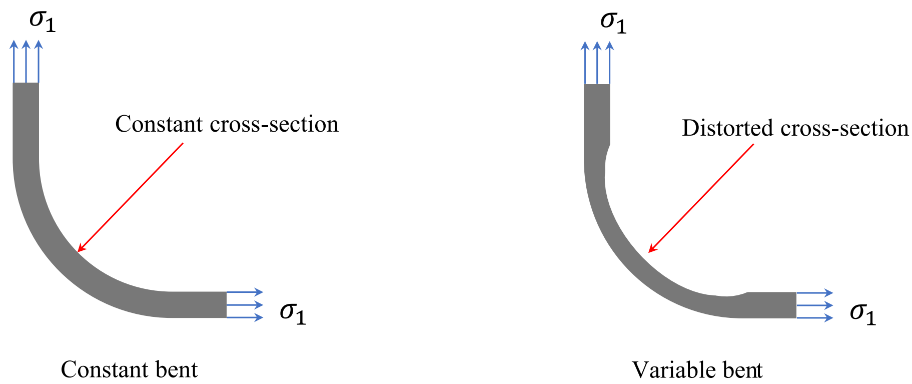


Fig. 11. Geometry of the bending bar.

used to investigate the fundamental principles of bond stress-deformation relationships by examining local bond slip.

Mehrabi [105] conducted unidirectional axial pullout tests to investigate the bond properties of 12.7 mm diameter thermoplastic GFRP bars to concrete. The results showed that the strength of 12.7 mm diameter thermoplastic GFRP bars bonded to concrete at 5–8 d bond length was 8.3–15.2 MPa, and the bond strength of the thermoplastic bar was comparable to that of the high-performance FRP bars using thermosetting polymers. Wang et al. [120] investigated the bond behavior of a two-component thermoplastic epoxy BFRP bar with concrete and compared it with thermoplastic GFRP bar and thermoset BFRP bar as shown in Table 5. The tests showed that the thermoplastic BFRP bar with deep ribs and a diameter of 8 mm (Groups 6 and 7) showed a positive correlation between bond strength and concrete strength due to the lack of interlaminar shear strength of the thermoplastic epoxy resin and the partial detachment and splitting of the bar. The failure mode of the members in the other groups was that the bars were pulled out without bar splitting, fracture or concrete splitting, where the bond strength of the thermoplastic BFRP bars with deep ribs was higher and close to the level of steel and thermoset bars (Groups 3, 9 and 10). As shown in Fig. 12, the bond strength of thermoplastic BFRP bar was approximately the same as that of thermoplastic GFRP bar, thermoset BFRP bar and steel bar. The bond-slip curves at the post-peak stage are also close to each other for thermoplastic and thermosetting FRP bars.

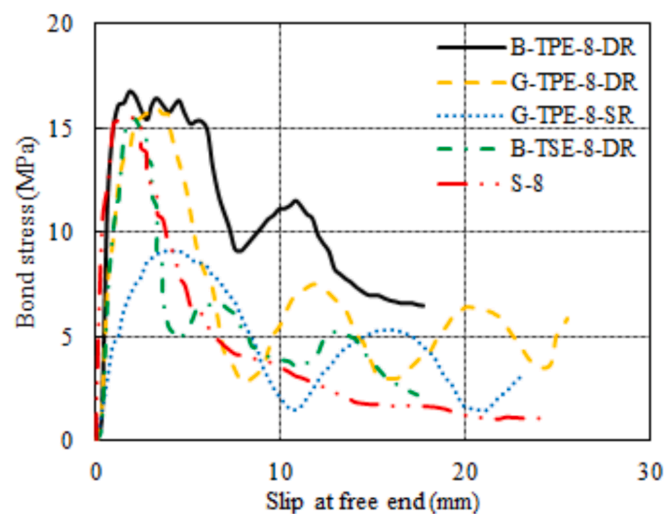


Fig. 12. Parametric comparison of bond stress-slip behavior [120].

Table 6 gives a comparison of the main experimental data with the corresponding limits specified in the latest standards such as the American standard (ASTM D7957/D7957M-17 [106]), the Canadian standard (CSA S807-19 [107]) and the Chinese standard (GB 50608-

Table 5
Experimental results of drawing tests [120].

Group number	Group ID	Failure mode	Pullout bond strength (MPa)/CV (%)	Corresponding slippage at loaded end (mm)	Corresponding slippage at free end (mm)	Calculated development length (mm)
1	G-TPE-8-DR	Rebar pulled out	15.8/1.3	4.13	6.43	171
2	G-TPE-8-SR	Rebar pulled out	9.0/17.7	2.49	5.35	300
3	S-8	Rebar pulled out	16.7/3.4	1.55	3.04	161
4	B-TPE-8-CR	Rebar pulled out	8.7/8.7	2.81	5.65	310
5	B-TPE-8-SPR	Rebar pulled out	10.6/11.6	2.87	5.44	254
6	B-TPE-8-DR (G30)	Rebar split	16.0/3.6	2.82	6.43	169
7	B-TPE-8-DR (G40)	Rebar split	19.2/4.7	3.67	6.46	140
8	B-TPE-8-SR	Rebar pulled out	10.8/12.5	3.89	6.52	250
9	B-TSE-8-DR	Rebar pulled out	17.7/16.7	1.82	4.29	147
10	B-TPE-16-DR	Rebar pulled out	12.3/4.4	3.01	4.77	n/a
11	S-16	Rebar pulled out	13.4/5.1	2.07	2.82	n/a

2020 [125]). Most of the properties of the bendable thermoplastic BFRP bars are qualified, proving their potential application in reinforced concrete structures. However, the interlayer shear strength needs special attention. The current CSA S807 [107] standard specifies the interlaminar shear strength limit for GFRP and BFRP bars, but it is still difficult for thermoplastic BFRP bars to reach this limit. Therefore, to improve the interlaminar shear strength, the fiber-resin interface processing and manufacturing methods need to be improved.

5. Durability of thermoplastic FRP bar

FRP bars may deteriorate under a combination of environmental aggressions such as moisture, temperature changes, ultraviolet (UV) radiation, elevated temperatures, alkaline environments, sustained mechanical loading (creep/relaxation), and fatigue cycling. During service, various design codes or standards often introduce an environmental degradation factor to account for the degradation of mechanical properties due to environmental attack [126,127]. The durability of conventional thermosetting FRP bar used in civil engineering has been extensively studied [128–136]. It has been found that although the deterioration of thermosetting FRP bar is related to a few factors, the exposure temperature is the most important factor influencing the deterioration process [137]. However, there is still very limited research on long-term durability of thermoplastic FRP bars.

Analytical and experimental studies of the long-term behavior of FRP bars can be divided into two categories [138]. The first category consists of the residual properties when exposed to various environments without loading. The second category includes the effects of continuous loading [139]. The durability of FRP bar is not only related to the strength of its constituent materials (fibers and matrix), but also to the integrity of the interface between these two components during aging. Aging of the interface reduces the load transfer between the fibers, thus weakening the strength of the FRP bar. Environmental attacks such as alkali may destroy the silicon-oxygen-silicon structure in fibers, subsequently a substantial loss of tensile strength of the fibers. Research has demonstrated that moisture, pH, and temperature are the primary parameters affecting the durability of FRP bar. The moisture absorbed by the FRP bar coupled with the temperature of the exposure creates stresses in the material that break down the fibers, matrix, and the interface between them, thereby gradually reducing the strength of the FRP bar over time. Although these tests are considered important for evaluating the long-term performance of FRP bar, only a few studies answer the main question of the combined effect of load and environment. Very limited studies have been conducted on thermoplastic FRP bar exposed to alkaline environments and loaded at different levels.

When loads are applied to FRP bar, the fibers carry the loads while the resin transfers the stresses between the fibers, and protects the fibers from ions in the environment, especially OH– in the interstitial solution of the concrete. The degradation mechanism of FRP bar is more complex than that of steel bar. Since the mechanical properties of FRP bar are controlled by the fibers [140], if the fibers are not degraded, the FRP bar can resist external loads. If the resin is eroded and degraded, the fiber surface begins to fracture and progresses to the interior of the bar, resulting in a reduction in bar strength. The interface between the fibers and the resin controls the resistance of the FRP bar to alkalis [141,142]. Improvement of the interfacial bond strength can effectively increase the alkali resistance of the FRP bars.

Micelli and Nanni [108] investigated the effects of thermoplastic GFRP bar specimens subjected to simulated concrete pore solutions and environmental factors including freeze–thaw, high relative humidity, high temperature and UV radiation. The results showed that the thermoplastic resin was not affected by solution diffusion in a significant extent, and the apparent transverse shear strength of the specimens decreased by about 30 % after 42 days of immersion in a simulated concrete pore solution at 60 °C.The retention of tensile properties of the specimens after immersion in the simulated concrete pore solution and after environmental cycling was 100 %. In contrast, the tensile strength of thermoset GFRP bar decreased to 70 % and 59 % after 21 and 42 days of immersion in an alkaline solution at 60 °C. Micelli and Nanni [108] found that thermoplastic GFRP bar exhibited higher alkaline resistance with a retention of tensile strength of about 87 % after immersing in an alkaline solution at 60 °C for 90 days, as shown in Fig. 13. These results also meet the minimum requirements of ASTM D7957 [106] and CSA S807 [107], and it is demonstrated that the alkaline resistance is very close to that of thermoset GFRP bar.

Zhou et al. [143] experimentally investigated the interlaminar shear strength (ILSS) of glass fiber reinforced polypropylene (GFRPP) bar by comparatively assessing its durability in distilled water (DW) and alkaline solution (AS) as well as in a simulated marine concrete environment. The results show that the alkaline resistance of GFRPP bars is significantly better than that of thermoset GFRP bars. The ILSS retention of GFRPP bars exposed to AS at 60 °C for 30, 75 and 120 days were 91.7 %, 77.0 % and 67.5 %, respectively, which were 1.03, 1.06 and 1.01 times higher than those exposed to DW, and 1.33 times higher than those of thermoset GFRP bars under the same conditions. They concluded that the hot and humid environment accelerated the development of micro voids and cracks in the GFRPP bar during the pultrusion process, which was the main cause of the long-term mechanical property degradation and fiber-resin debonding. Further studies on

Table 6
Mechanical properties tested and limit values in standards [120].

Property (Mean value)	Group ID in tests			Specified limits		
	B-TPE-8	G-TPE-8	B-TSE-8	ASTM D7957 [106]	CSA S807 [107]	GB 50608 [125]
Tensile strength (MPa)	1348	1145	1297	843	1000	800 for basalt 700 for glass
Tensile elastic modulus (GPa)	52.3	51.9	48.8	44.8	50 for basalt 40 for glass	50 for basalt 40 for glass
Tensile fracture elongation (%)	2.58	2.25	2.66	1.1	n/a	1.6 for basalt 1.8 for glass
Transverse shear strength (MPa)	150	107	172	131	160	N/A
Interlaminar shear strength (MPa)	23.4	20.3	34.8	n/a	35	N/A
Bond strength (MPa)	16.0	15.8	17.7	7.6	10	N/A

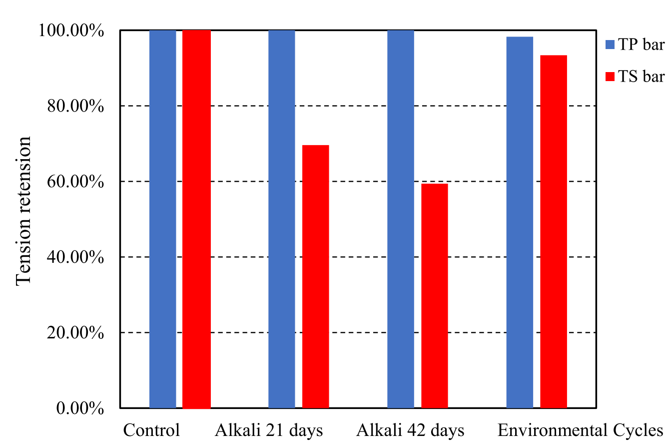


Fig. 13. Comparison of durability of thermoplastic bar (TP bar) and thermoset bar (TS bar) [108].

durability of thermoplastic FRP bars need to be conducted to gain in-depth understandings.

Benmokrane et al. [51] studied typical micrographs of the bars at different magnifications, as shown in Fig. 14. Although a few voids with very low porosity were observed on the surface of TP specimens, it indicates that the fibers in TP and TS bars are uniformly distributed. Fig. 15 shows SEM micrographs at higher magnifications, highlighting the fiber-resin interface in the TP and TS specimens. No defects were detected in the polymer matrix, glass fibers, or interfaces of either bar type. Therefore, the bonding between the glass fibers and the thermoplastic resin is considered adequate, with no gaps detected at the interface.

Ibrahim et al. [109] studied the durability of the new TP bars in an alkaline environment and compared them with the TS bars. Fig. 16 shows typical micrographs of the alkaline-treated TP and TS bars. The interface between the fibers and the resin matrix showed no signs of debonding, with no gaps, voids, or deterioration detected. Additionally, the tensile strength properties were tested after being conditioned in an alkaline solution for 90 days at 60 °C. The results showed that both the conditioned new TP bars and the TS bars exhibited nearly linear behavior up to failure, with average tensile strength retention of 92 % and 81 %, respectively. This indicates that the new TP bars retained a significant portion of their tensile strength even after environmental aging. Furthermore, the tensile modulus of both bar types was not significantly affected, with the new TP bars and TS bars having average retention rates of 99 % and 100 %, respectively. This indicates that these bars maintained their stiffness and elasticity even after exposure to the alkaline environment.

6. Reinforced concrete (RC) elements reinforced with thermoplastic FRP bars

FRP bar is an ideal internal bar for concrete structures requiring durability in harsh environmental conditions and is competitive as bar for concrete elements. Garnaut [144] states that if builders are unable to assess the reliability of a new technology product, they may avoid it in favor of more familiar, older, and less efficient products. To encourage its development and use, the behavior of FRP reinforced concrete structures should be better understood to ensure that the design and use of this new technology can be designed and used with sufficient reliability.

D'Antino et al. [145] investigated the flexural tests of concrete beams reinforced with conventional steel bars and thermoset or thermoplastic resin GFRP bars. Four beams were tested, each reinforced with the same type of longitudinal and transverse (i.e., hoop) reinforcement. All beams had the same cross-sectional area of longitudinal reinforcement. Besides the beams reinforced with steel bars, one beam was reinforced with straight longitudinal thermoset GFRP bars, one with straight longitudinal thermoplastic GFRP bars, and one with longitudinal thermoplastic GFRP bars bent at the ends. The geometry of the tested beams is shown in Fig. 17.

The test results show that the beam reinforced with steel bar (B-S-s-1) exhibits ductile behavior with significant deflection and many vertical cracks occur in the central portion of the beam as shown in Fig. 18(a). The applied load-vertical displacement curve is shown in Fig. 19. Cracking of the concrete occurred, followed by yielding of the longitudinal reinforcement when the load was 27.80 kN. The peak load was 190.17 kN and the vertical displacement was 58.79 mm.

The beam reinforced with thermoset GFRP straight bars, i.e.,

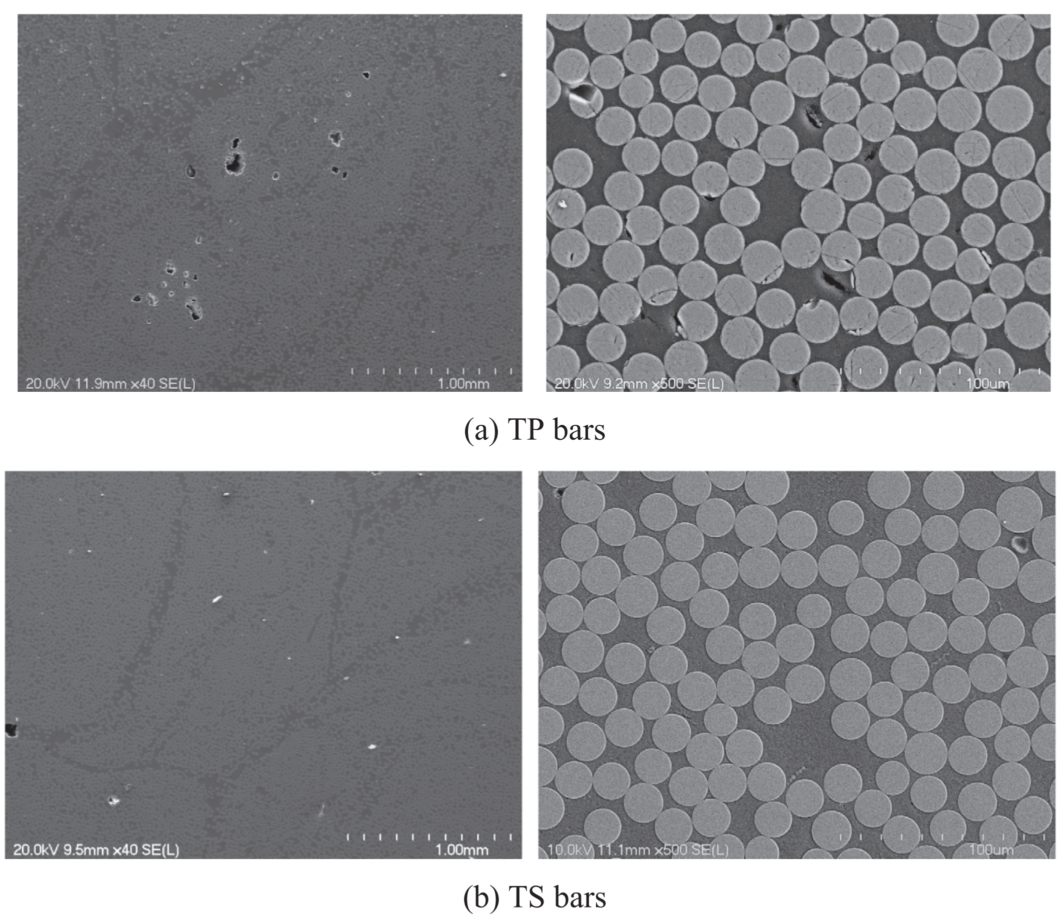


Fig. 14. Micrographs of (a) TP and (b) TS bars [51].

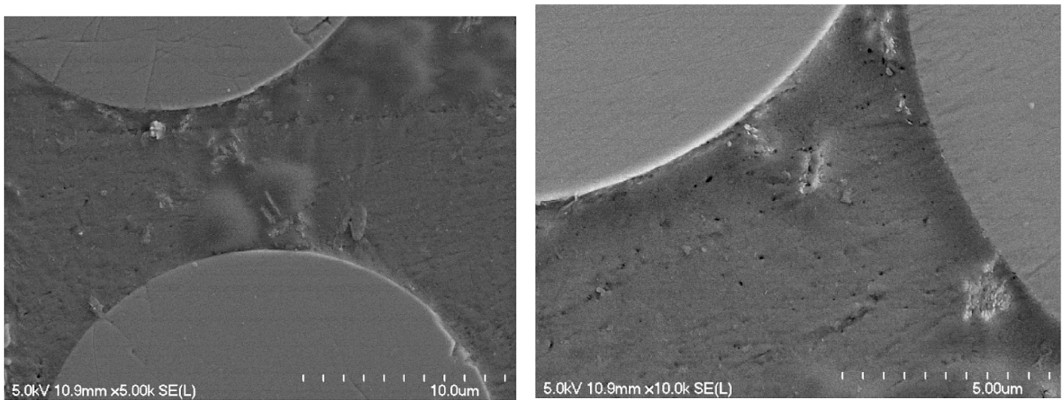


Fig. 15. Micrographs of TP bars at the fiber–matrix interface [51].

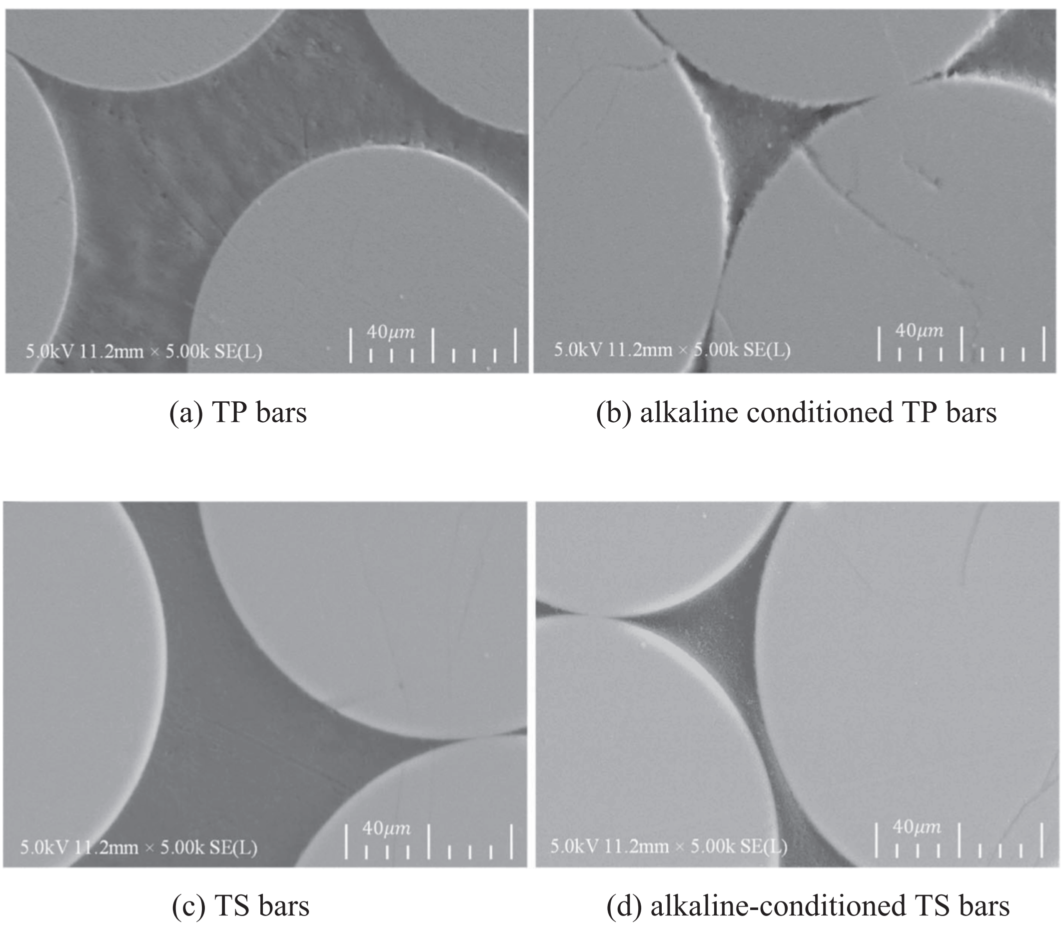


Fig. 16. Typical SEM results for the bars alkaline conditioned bars [109].

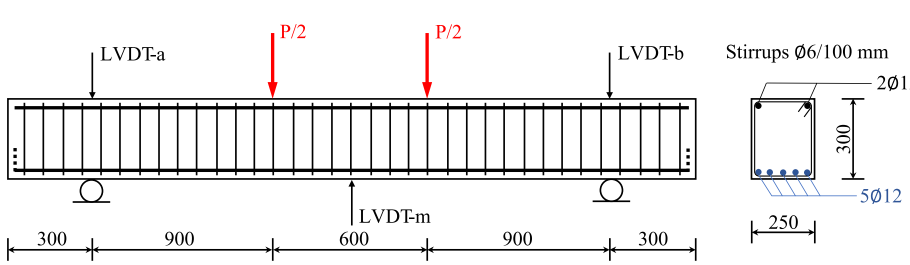
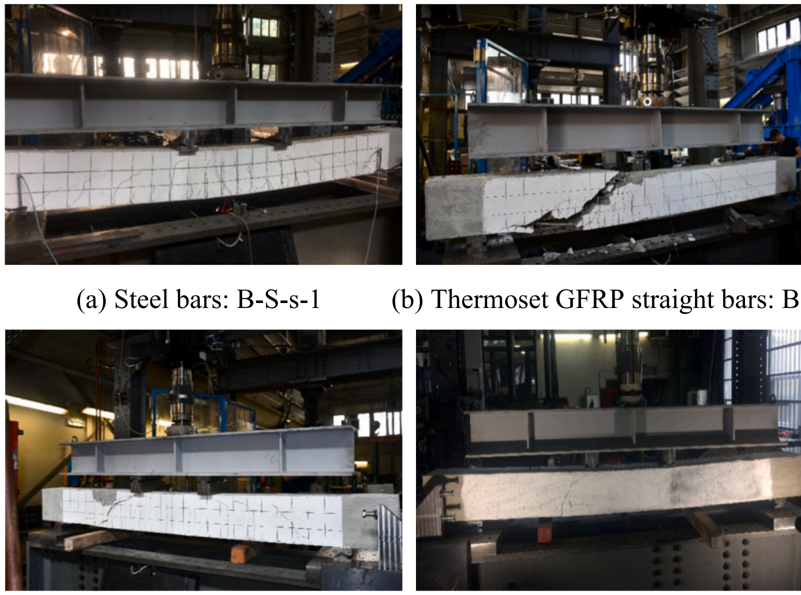


Fig. 17. Geometry of test beam (mm) [145].



(a) Steel bars: B-S-s-1 (b) Thermoset GFRP straight bars: B-TS-s-1

(c) Thermoplastic GFRP straight bars: B-TP-s-1 (d) Thermoplastic GFRP bent bars: B-TP-b-1

Fig. 18. Damage of beams reinforced with different types of bars [145].

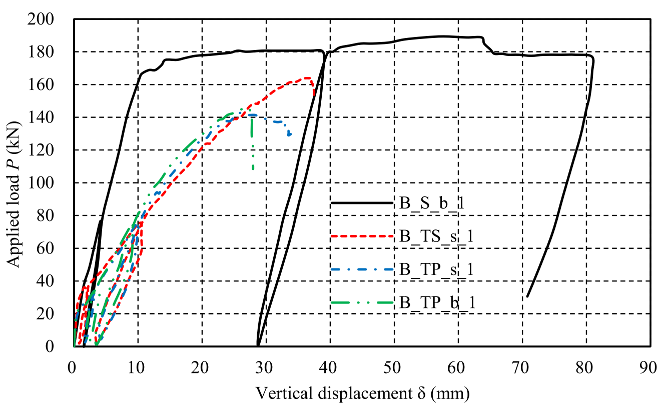


Fig. 19. Applied load versus vertical displacement curves for test beams [145].

specimen B-TS-s-1, showed a similar initial behavior as beam B-S-s-1, with vertical cracks concentrated between the loading points, as shown in Fig. 18(b). In addition, the first cracking of the concrete occurred at an applied load value of 29.20 kN similar to that of beam B-S-s-1, as shown in Fig. 19. After the first cracking of the concrete, the deflection of beam B-TS-s-1 was higher than the deflection of the reinforced concrete beam under the same load as the machine stroke increased, due to the fact that the modulus of elasticity of GFRP is lower than that of steel. At the application of a load of 164.93 kN, the main shear crack opens and eventually leads to damage, as shown in Fig. 18(b).

The beams reinforced with thermoplastic GFRP bars using straight bar B-TP-s-1 and bending bar B-TP-b-1 showed a similar behavior to the beam B-TS-s-1, with the appearance of vertical cracks in the central part of the beams, which were eventually damaged due to the appearance of the main shear cracks as shown in Fig. 18(c) and (d). The load responses obtained were similar to those of specimen B-TS-s-1, with some minor differences: 1) the loads associated with the first cracking of the concrete were slightly lower than those observed in beams B-TS-s-1 and B-S-s-1, as shown in Fig. 19; 2) the loads associated with the shear damage were slightly lower than those of beams B-TS-s-1. They suggested that these differences could be caused by the thermosetting and thermoplastic GFRP bars with different bond behavior. The results obtained show that for the same bond length, the thermoplastic GFRP bars produce lower tensile stresses than the corresponding thermoset GFRP bars for the same value of interfacial slip. The results show that bending the ends of the longitudinal thermoplastic GFRP bars does not affect the response of the beams.

7. Conclusions

In this study, the advantages and disadvantages of thermoplastic FRP bars in achieving sustainable development and convenience in effective secondary processing of the bars on-site are presented and discussed. The paper summarizes the results of the current research on the mechanical, durability and creep properties of thermoplastic FRP bar. The following main conclusions can be summarized:

(1) Epoxy, vinyl ester and unsaturated polyester resins are the most used thermosetting resin matrix for FRP bars. However, the thermosetting resins currently used generate a large amount of waste due to the difficulty of recycling, which poses a challenge to both the cost and the environment, and this is a key issue that needs to be further addressed. However, the growing demand for sustainability and recyclability is driving FRP bar manufacturers to switch to thermoplastic resins.
(2) Unlike conventional thermosetting FRP bars, thermoplastic FRP bars not only have greater elongation, but also exhibit similar mechanical properties to thermosetting FRP bars. Since thermoplastic FRP bars can be recycled and processed at the construction site, it is more environmentally friendly and cost-effective than traditional thermosetting FRP bars.
(3) The long-term creep strain of thermoplastic GFRP bars is basically the same as that of thermoset GFRP bars.
(4) The existing tests on bent thermoplastic FRP bars reveal that the strength retention of the bent segment is better than that of thermosetting FRP bars. The mechanical properties of the bent part of the thermoplastic FRP bars should be further improved.
(5) Few studies have been conducted on the bond behavior between concrete and thermoplastic FRP bars. Existing studies reveal that the bond strengths between concrete and thermoplastic or thermoset FPR bars are comparable.

(6) Thermoplastic FRP bars have good durability to alkaline environments, and their alkali resistance is close to that of thermosetting FRP bars, proving that they can be used as concrete reinforcement materials.

8. Future research

With the continuous development and innovation in FRP bar production technology, thermoplastic FRP bars have become increasingly popular. To better utilize the advantages of thermoplastic FRP bar and promote the wide application of thermoplastic FRP bar in engineering structures, further studies on many aspects of thermoplastic FRP bars are necessary.

(1) The performance of FRP bars made of different types of thermoplastic resins varies greatly, so more research is needed on the fabrication technology and mechanical properties of thermoplastic FRP bars with different resin matrixes. Advancements on fabrication technology of thermoplastic FRP composites are necessary to increase the fiber content so as to enhance the mechanical properties of thermoplastic FRP composites.
(2) The existing research on the bonding performance of thermoplastic FRP bars with concrete is relatively rare, and the influence of other factors on the bonding performance, such as the concrete strength grade, bar diameter, surface treatment form and bond length, needs to be further studied.
(3) One of the advantages of thermoplastic FRP bars is impact resistance. Unlike thermosetting FRP bar, thermoplastic FRP bars have extremely strong impact resistance, and they can absorb vibrations and impacts better than thermosetting FRP bars, while no study has been found on the impact resistance of thermoplastic FRP bars.
(4) The durability study of thermoplastic FRP bars in harsh environment such as acid, alkali and salt without or with a constant stress is very limited, and the relationship between the durability performance of thermoplastic FRP bar in harsh environment and each influence parameter needs to be studied in depth.
(5) A simple and feasible bending device that will not significantly degrade the strength of the bent segment for shaping thermoplastic FRP bars in-site need to be developed. Approaches such as 3D printing of continuous fiber-reinforced thermoplastic plastics for better fiber arrangement and resin distribution at the bent segment can be established to guarantee the strength of the bent bars.
(6) The creep performance and creep limit fracture strength performance for thermoplastic FRP bars needs to be further studied.
(7) The short-term and long-term performance of structural concrete members reinforced with thermoplastic FRP bar needs to be explored in the future.
(8) Thermoplastic FRP bar is easier to realize the connection of reinforcement than thermosetting FRP bar in terms of welding technique. By controlling the welding temperature and time, it is also possible to weld thermoplastic FRP bars to metal. Establishment of welding method and research in this field are in urgent needs.
(9) The recycling of the components in thermoplastic FRP composites is worth studying to achieve sustainable development.
(10) Thermoplastic FRP uses thermoplastic resins, which are generally more expensive than thermoset resins. The processing requires high temperature heating equipment, increasing equipment costs and energy consumption. However, it offers advantages in on-site processing, transportation, and long-term maintenance. Therefore, further research is needed to compare the economic costs of both thermoplastic and thermoset FRP in practical engineering applications.

CRediT authorship contribution statement

Jun-Jie Zeng: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Sheng-Zhao Feng:** Writing – original draft, Investigation, Formal analysis. **Bin Zhao:** Writing – review & editing, Supervision, Resources, Conceptualization. **Feng-Yi Wu:** Writing – original draft, Investigation. **Yan Zhuge:** Writing – review & editing, Supervision, Methodology. **Hao Wang:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data, models, and code generated or used during the study appear in the submitted article.

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