Thermoplastic Composite Rebar Durability and Mechanical Testing

TIDC Project 2.25 – Final Report

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October 30, 2025

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Abstract

This research investigated the viability of novel glass-fiber reinforced thermoplastic (TP) composite rebars, manufactured using a continuous forming process, as a potential field-bendable and corrosion-proof alternative to conventional steel and commercial glass-fiber reinforced thermoset (TS) rebars. The study focused on TP composites using polybutylene terephthalate (PBT), polyamide-12 (PA12), and polypropylene (PP), evaluating their physical, mechanical, and thermal properties based on industry standards (ACI, AASHTO, ASTM). TP bars were manufactured using a continuous forming process. Baseline characterization identified GF+PBT composites as the most promising, performing comparably to TS rebars, though results indicated a need for improved matrix consolidation. Durability was assessed via immersion in high-pH alkaline solutions (pH 12.6-13.0) at elevated temperatures (up to 80°C). Unlike TS rebars which showed minimal degradation, the GF+PBT bars exhibited significant strength loss and matrix degradation, linked to high moisture uptake. This highlights a critical need for improved matrix chemical resistance and lower void content. Overall, GF+PBT rebars show significant promise but require further optimization in processing and matrix formulation to improve chemical resistance.

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Introduction

Reinforcement is used in concrete structures to increase its strength, control cracking, enhance durability, and accommodate structural load changes, thereby improving the toughness and flexural strength of the structure. Steel reinforcement has been most widely used in reinforced concrete due to its long and proven track of well-established performance and availability [1], [2]. However, steel reinforcement is highly susceptible to corrosion. Corrosion-related deterioration reduces structural performance, which significantly impacts the durability and service life of reinforced concrete (RC) structures, particularly in aggressive environments such as marine structures, bridges and industrial zones making it a pressing concern for civil engineers [3]. The repair and maintenance costs associated with steel corrosion impose a significant economic burden on the construction industry.

To address these challenges, Fiber-Reinforced Polymer (FRP) rebars have emerged as promising alternative reinforcement material. FRP rebars has gained significant attention from researchers and engineers for their enhanced durability. FRP rebars offer several advantages over steel, including corrosion resistance, lightweight properties, and high tensile strength[4] . In corrosion-prone environments, or structures where ultimate tensile strength is more critical than ductility, FRP rebar is an excellent choice.

Among FRP systems, thermoset based Glass Fiber Reinforced Polymer (GFRP) rebars have been widely adopted in civil infrastructure, particularly in corrosive environments. These thermoset rebars, typically manufactured using pultrusion processes, are governed by design standards such as ASTM D7957 [5] and recently ASTM D8505 [6] for higher modulus FRP bar. Thermoset (TS) FRP rebars have been incorporated into projects across North America under design guidance from ACI 440.1R [7], AASHTO [8] and other regulatory bodies. Despite their success, thermoset rebars are limited by inherent brittleness, non-recyclability, don't have ability to be reshaped after curing, posing challenges during field adjustments. In contrast, thermoplastic matrices offer improved impact resistance, recyclability and potential for reshaping after manufacturing. However, the manufacturing process of thermoplastic composites is notably more intricate and costly compared to traditional thermoset manufacturing due to high processing viscosities [4].

Recent advancements in Continuous Forming Machine (CFM) technology at the University of Maine's (UMaine) Advanced Structures and Composites Center (ASCC) have enabled the efficient, low-emission, automated production of Thermoplastic Glass Fiber Reinforced Polymer (TP GFRP) rebars. These rebars use commercially available pre-saturated feedstocks, bypassing resin saturation challenges and enabling large-scale production [9]. These innovations align well with current global initiatives in sustainable construction and green manufacturing.

Fiber-reinforced polymer (FRP) refers to a type of composite material wherein a polymer is strengthened through the incorporation of fibers [4]. The primary components of FRP are:

Fibers: Provides tensile strength and stiffness. (e.g., glass, carbon, basalt, aramid fibers)

Polymer Matrix: Protects fibers from environmental degradation and distributes stress among fibers. (e.g., thermoset and thermoplastic resins)

Extensive research has advanced the understanding of the behavior and performance of concrete members internally reinforced with FRP bars [12], [13]. FRP reinforcing bars became commercially viable solution as internal reinforcement to concrete structures in the late 1980s, driven by growing demand for nonferrous, electromagnetically transparent reinforcement in concrete structures [14]. The use of FRP rebars in civil infrastructure has grown significantly over the past two decades. Countries like Canada, Japan, United States, and several European countries have incorporated FRP reinforcement into bridges, marine structures, and highway pavements due to its long-term durability and lower life-cycle costs [12].

The Highway 40 Overpass in Quebec, Canada, was reinforced with FRP rebars instead of steel to showcase the viability of composite reinforcement in highway infrastructure [15]. Glass Fiber Reinforced Polymer (GFRP) rebars were used in seawalls and marine structures in the port of Maimi, Florida, USA to prevent saltwater corrosion, significantly reducing maintenance costs while preserving structural integrity [14]. The AASHTO LRFD Bridge Design Specifications [8] and the Canadian Highway Bridge Design Code [16] include design provisions for concrete bridge members reinforced with FRP bars, leading to the design and construction of over 500 bridges across Canada and the USA using FRP reinforcement [17]. E.g., Nipigon River Cable Stayed Bridge, Haals River Bridge replacement, Eagle River bridge, etc. [18]. In 2018, Saudi Arabia constructed a 21.3 km flood mitigation channel, the world's largest GFRP-reinforced concrete structure, using 10 million linear meters of GFRP bars and 188,000 m^3 of structural concrete [19]. The use of high strength, noncorroding GFRP bars was essential due to the project's proximity to an industrial zone with exposure to aggressive chemicals and hydrocarbons.

Thus, they are increasingly used in bridges, marine structures, and other applications where durability is critical [14]. The construction industry is gradually embracing FRP rebars as a viable alternative to steel, particularly in corrosion-prone environments. Advances in material technology, regulatory acceptance, and sustainability concerns are expected to further drive the adoption of FRP rebars in the coming years.

The most common types of fiber used in civil engineering applications are glass, carbon, aramid and basalt [14]. Glass fibers stands out as the most commercially viable option for reinforcement in FRP composites industry due to their favorable balance of mechanical properties and cost of manufacturing [20]. Glass Fiber reinforced Polymer (GFRP) offers excellent electrical insulation, corrosion resistance, high strength, and durability. With optimized fiber orientation and composition, they can achieve stiffness comparable to steel and higher strength at a lower density, making them a highly cost-effective reinforcement option [4]. Thus, GFRP rebars have become essential material in modern construction.

Among the available glass fiber types, E-glass is widely used for its affordability and strength, while S-glass offers superior mechanical properties at a higher cost. AR-glass, with high alkali resistance, is suited for use in concrete environments but faces challenges in thermoset resin compatibility [14]. However, E-CR glass fibers are now widely used in commercial GFRP rebar manufacturing due to their superior durability in aggressive environments. Unlike conventional E-glass, E-CR glass fibers offer enhanced chemical resistance, comparatively superior in acidic conditions [21]. They are manufactured in compliance to ASTM D578 [22] standards without boron and fluorine elements present in E-glass which contribute to improved durability and thermal stability [22], [23].

While fibers play the primary role in providing elastic modulus and strength, the choice of resin matrix is also crucial during the manufacturing process as it affects the mechanical properties of composites. Matrix is a binding agent in FRP composites which serves as bridge between the fibers, bringing them together in resisting loads [24]. In demanding applications, high-performance matrices are needed to deliver specific characteristics. These matrix materials must exhibit excellent dimensional stability at elevated temperatures, strong thermal resistance, low moisture uptake, superior chemical resistance, high mechanical strength, outstanding stiffness, and robust compressive strength[25]. Typically, FRP matrices are categorized into two main types: thermoset and thermoplastic polymers.

Thermoset resins, such as epoxy, polyester, and vinyl ester, currently dominate the FRP composites market. They offer advantages such as structural rigidity, chemical resistance, lower viscosity, ease of processing, and higher production efficiency [24]. However, their irreversible curing process results in limited recyclability, posing significant challenges for sustainability and end-of-life management. Additionally, thermoset rebars cannot be reshaped after curing, requiring reinforcement shapes like hooks and stirrups to be pre-formed during manufacturing. Thermoset FRP rebars are governed by standards such as ASTM D7957 [5] and ASTM D8505 [6].

Thermoplastic polymers, on the other hand, represent an emerging class of matrix materials, characterized by their remarkable impact resistance [4], recyclability with minimal impact on mechanical performance [4], [24] and adaptability during construction. Unlike thermosets, thermoplastics do not cross-link during curing, allowing them to be reheated and reshaped as needed. This reprocess-ability enables field bending of composite rebar, offering a distinct advantage in construction scenarios requiring on-site flexibility. Nevertheless, their manufacturing complexity leads to higher production costs, attributable primarily due to high processing viscosity challenges compared to conventional thermoset matrices for fiber saturation and composite integrity[4]. The most used thermoplastic resins include polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyamide (PA), polycarbonate (PC), and polyetheretherketone (PEEK).

Conventional fiber-reinforced polymer (FRP) rebars are commonly manufactured using pultrusion, a continuous process where dry fibers are pulled through a resin bath and a heated die to form solid profiles[4] and has surface profiles or deformations made with secondary manufacturing processes. This method is efficient for thermoset resins such as epoxy and vinyl ester, but it is less suitable for thermoplastics due to their high viscosity and slow fiber wet-out behavior.

To overcome these challenges, the University of Maine’s Advanced Structures and Composites Center developed the Continuous Forming Machine (CFM)_a novel thermoplastic composite forming system designed to produce lineal FRP profiles with consistent geometry and high throughput. It can produce structural members at speed of up to 4m/min[27]. The CFM utilizes pre-impregnated or commingled continuous fiber-reinforced thermoplastic tapes, which are processed through infrared heating, modular forming dies, and rapid cooling systems [9], [27]. The forming zone is adjustable and allows integration of secondary shaping steps such as roll forming or filament winding. Unique to thermoplastic composites, these rebars can be reheated and reshaped in the field with the simple application of the heat for use as stirrups, hooks, or ties, offering unprecedented flexibility during construction [9]. Haller et al. [27] validated this field adaptability by demonstrating the successful reheating and reshaping of thermoplastic composite rebars. Ongoing research focuses on optimizing suitable thermoplastics with required physical, mechanical and durability performance, surface texture and deformation addition for reinforced concrete applications. GFRP composite bars made from H^2 GF and thermoplastics PBT, PA12, and PP thermoplastic systems were manufactured and tested for physical properties, mechanical, thermomechanical and durability performance which is included in this thesis.

To ensure structural reliability, safety, and performance, composite rebars must conform to established national standards and guidelines. ASTM D8505[6] “Standard Specification for Basalt and Glass Fiber Reinforced Polymer (FRP) Bars for Concrete Reinforcement” outlines the qualification and testing requirements for high modulus fiber-reinforced polymer (FRP) bars intended for use in concrete reinforcement, including key performance criteria and standardized test methods. This standard defines essential physical, mechanical, and durability requirements for qualifying and certifying FRP bars. In addition, the American Concrete Institute (ACI), through documents such as ACI 440.1R[7] “Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars” and ACI 440.3R[28] “Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures.” , provides widely accepted guidelines for the design, construction, and testing of FRP reinforcement in concrete structures. ACI documents also complement ASTM testing standards by bridging material qualification with structural design applications. Recommendations from the American Association of State Highway and Transportation Officials (AASHTO[8]) are also relevant, particularly for applications involving transportation infrastructure, emphasizing durability, load resistance, and long-term performance. Where direct design methodologies are not fully established, AASHTO refers to ACI and ASTM guidance as interim standards for material specification and performance benchmarking. Adherence to these standards ensures that FRP rebars are evaluated consistently and meet the necessary requirements for safe and effective structural use.

Although thermoplastic composite rebars offer compelling benefits over traditional thermoset rebars, currently, the challenge lies in developing thermoplastic composite rebars through feasible thermoplastic polymers that meets physical, mechanical, durability standards and improved bond performance with concrete for structural applications. There is also lack of comprehensive data on thermomechanical performance and insufficient understanding of long-term durability of thermoplastic composite bars. Although, some studies have been conducted on Elium-based high performance engineering thermoplastics for structural applications manufactured due to their high glass transition temperatures (Tg ~ 100 °C), common engineering thermoplastics with lower Tg such as polybutylene terephthalate (PBT), polyamide 12 (PA12), and commodity thermoplastics polypropylene (PP) have not been explored. Composite rebars manufactured from these thermoplastics have not been systematically investigated, motivating this study to assess their viability for reinforced concrete applications. For broader code approval and structural adoption, it is essential to assess the mechanical performance and durability of TP composite bars under conditions relevant to reinforced concrete applications. The research is also to evaluate the TP composite bars to the performance of commercial TS composite bars for competitive acceptance to the construction industry. In addition, current standards and testing protocols primarily developed for thermoset systems may not directly apply to thermoplastic composites, underscoring the need for the development of standards that also address thermoplastic materials. These studies form a core component of this master's thesis work, contributing to the development of cost-effective, sustainable, recyclable, and field-adaptable reinforcement technologies.

Methodology

This research was structured to systematically evaluate the viability of novel thermoplastic (TP) rebars against the current industry-standard thermoset (TS) rebar. The methodology involved manufacturing candidate materials, subjecting them to baseline characterization and accelerated aging, and then performing a series of standardized tests to measure their performance.

Materials and Specimen Selection

The study evaluated several composite materials to provide a comprehensive comparison:

Thermoplastic (TP) Rebars:

Three different glass fiber reinforced TP composite systems were manufactured using glass fibers with:

1. **Polybutylene terephthalate (PBT)**
   Polybutylene terephthalate is a mid-range engineering thermoplastic of polyester polymer group, offering a good balance of mechanical strength, thermal stability, and reasonable cost.
2. **Polyamide-12 (PA-12)**
   Polyamide 12 is a higher-performance engineering thermoplastic of polyamide polymer group, known for its toughness, good chemical resistance, and low moisture absorption (compared to other nylons).
3. **Polypropylene (PP)**
   Polypropylene is a very low-cost, high-volume commodity plastic of polyolefin polymer group known for its excellent chemical resistance.

These were selected to investigate a range of economical and potentially field-bendable materials. The bars were produced using a Continuous Forming Machine at the University of Maine's Advanced Structures and Composites Center (ASCC). Figure 1 shows the CFM equipment at ASCC highlighting the different components of the machine that aid in manufacturing of glass fiber reinforced thermoplastic rebars from continuous fiber reinforced thermoplastic tapes.

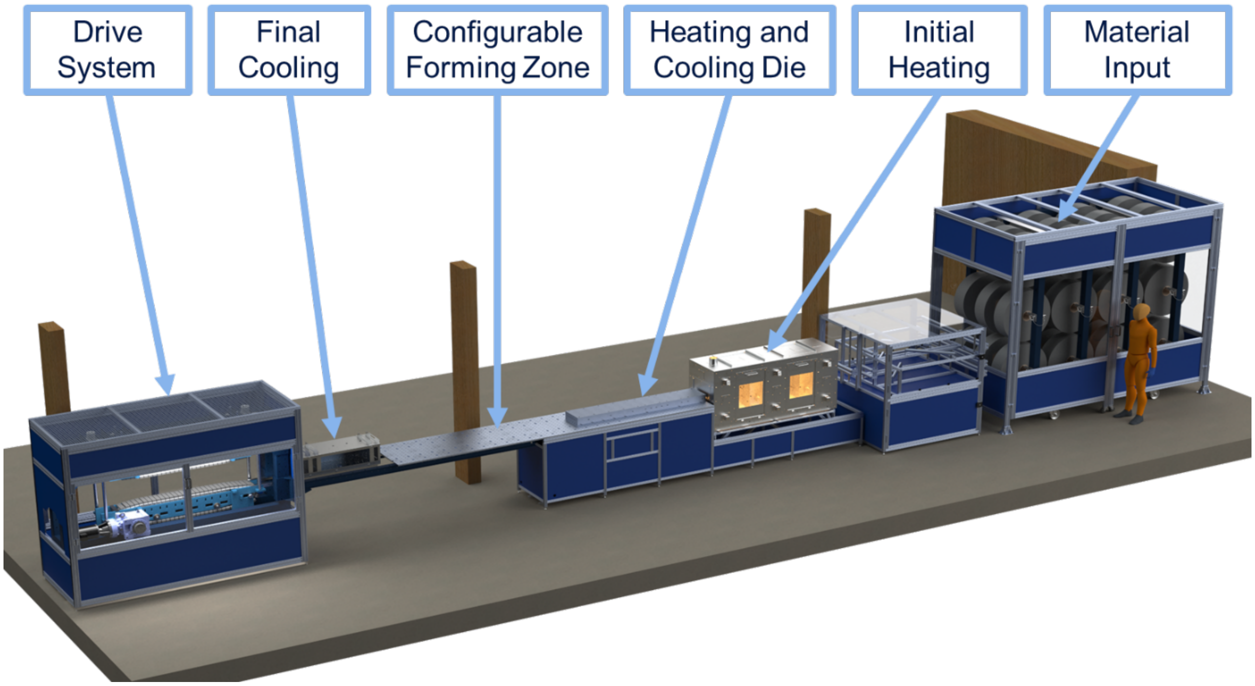

Figure 1: Continuous Forming Machine at ASCC, UMaine.

Thermoset (TS) Rebar:

Two traditional, commercially available thermoset GFRP rebars were included in the study.

1. Mateenbar (TS1)
2. VRod-60 (TS2)

This specimen was selected to act as a baseline control. Since TS rebars are already standardized and used in bridges today, this allows for a direct comparison of how the novel TP materials perform against the current industry standard.

Figure 2 shows the composite rebar specimens used in the study.

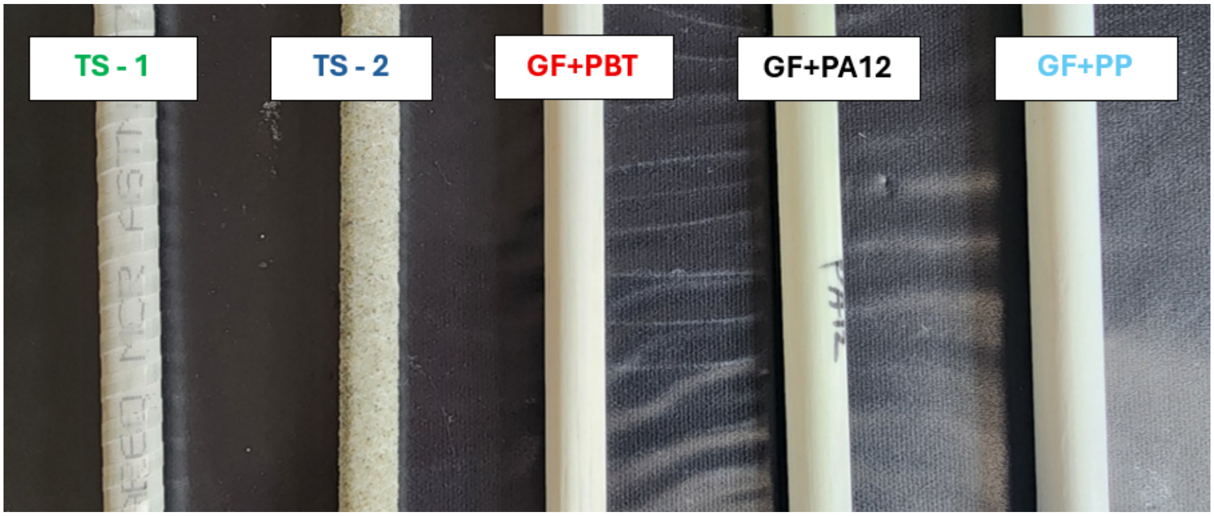

Figure 2: GFP bar specimens used in the study.

Testing Procedures and Industry Standards

A comprehensive suite of tests was completed on both control (un-aged) and aged specimens to characterize their performance in line with industry standards.

Baseline Characterization

All specimens were first tested for fundamental physical and mechanical properties, including:

- Cross-sectional area (ASTM D7205) and density (ASTM D792)
  ASTM D8505 requires a minimum cross-sectional area of 119 mm^2 and a maximum cross-sectional area of 169 mm^2 for #4 rebars.
- Fiber content (ASTM D3171) and void content
  ASTM D8505 requires a minimum fiber mass content of 70%.
- Tensile properties (ASTM D7205)
  ASTM D8505 requires a minimum tensile modulus of elasticity of 60 GPa and a minimum guaranteed ultimate tensile strength of 124 kN for #4 rebars.

Figure 3 shows the grouting system used for tensile testing of the rebars.

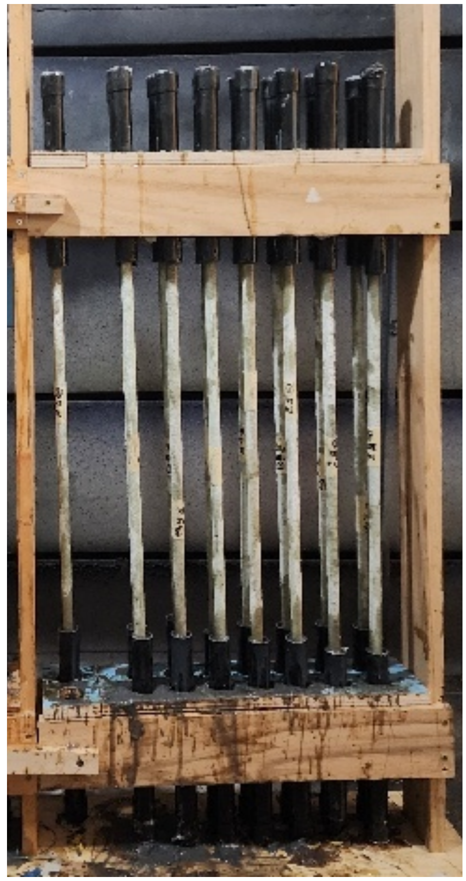

Figure 3: Grouting system used for tension test of rebars.

- Transverse shear strength (ASTM D7617) and apparent horizontal shear strength (ASTM D4475)
  ASTM D8505 requires transverse shear strength of 152 MPa and a minimum apparent horizontal shear strength of 37.9 MPa.

These tests are directly related to the qualification criteria specified in ACI and AASHTO design codes and their referenced ASTM standards (D7957 and D8505), which are the governing documents for using FRP rebar in structural concrete.

Accelerated Aging and Field Relevance

To simulate the long-term effects of embedment within a concrete structure, an accelerated aging protocol was implemented. Mean moisture absorption was measured using ASTM D570. ASTM D8505 requires mean moisture absorption to be less than 0.25% in 24 hours at 50°C and less than 1.0% to saturation at 50°C.

Mean alkaline resistance was characterized using ASTM D7705, procedure A. ASTM D8505 requires the mean ultimate tensile force to be greater than 80% for initial mean ultimate tensile force following 90 days at 60°C.

This durability assessment involved two key conditioning measures:

- Chemical Environment: Specimens were immersed in a high-pH alkaline solution (pH 12.6-13.0). This environment was chosen because it is highly relevant to field conditions, as it accurately mimics the caustic, alkaline pore solution of wet concrete.
- Thermal Acceleration: The immersion was conducted at various temperatures (room temperature, 60 °C, and 80 °C. According to principles of chemical kinetics, the elevated temperatures accelerate the rate of degradation mechanisms, such as moisture uptake and chemical attack on the matrix and fibers. This allows short-term lab tests (30 and 60 days) to correlate to and simulate long-term exposure (e.g., 25-50 years) in a real-world bridge deck.

Discussion of Results

Performance Targets and Control Specimen Results

The target test values for the specimens were those specified by the ASTM standards for qualifying composite rebars.

The control (un-aged) specimens performed well. The GF+PBT composite bars demonstrated the most promising performance among the new thermoplastic systems. These control specimens successfully met the ASTM standards for baseline properties and performed comparably to the traditional thermoset rebar, validating their potential as a viable alternative.

Table 1 shows the conversion from units used in the study to imperial units as a reference to the readers of this report.

Table 1: Conversion from units used in the study to imperial units.

Quantity	Units used in study	Imperial units
Length	25.4 mm	1 inch
Density	1 g/cm^3	62.4 lb/ft^3
Force	1 KN	0.224 kipf
Strength	1 MPa	0.145 ksi
Modulus	1 GPa	0.145 Msi

Table 2 shows the measured cross-section area of the rebars used in this research work.

Table 2: Measured Cross-sectional Area for #4 GFRP bars.

	Measured Cross-sectional Area (mm^2)	Effective Diameter (mm)	Coefficient of Variation (± %)
Commercial Thermoset Rebars			
TS-1	150	13.8	0.077
TS-2	148	13.8	0.34
Thermoplastic Smooth Bars			
GF + PBT	161	14.3	0.084
GF + PA12	163	14.4	0.22
GF + PP	165	14.5	0.046

Table 3 shows the density of the GFRP bars used for this study.

Table 3: Density for #4 GFRP bars.

	Density (gm/cm^3)	Coefficient of Variation (± %)	Density of UD tape (gm/cm^3)
Commercial Thermoset Rebars			
TS-1	2.16	0.10	--
TS-2	2.13	0.57	--
Thermoplastic Smooth Bars			
GF + PBT	2.06	0.11	2.19
GF + PA12	1.87	0.15	2.10
GF + PP	1.91	0.13	2.01

Table 4 shows the fiber content of the rebars.

Table 4: Measured Fiber Content of #4 GFRP bars.

	Fiber Mass Content (%)	Coefficient of Variation (± %)	Fiber Mass Content of UD tape (%)
Commercial Thermoset Rebars			
TS-1	84.3	0.071	---
TS-2	85.1	0.075	---
Thermoplastic Smooth Bars			
GF + PBT	81.3	0.04	81
GF + PA12	82.9	0.21	84
GF + PP	84.7	0.12	84

Table 5 shows the fiber volume content, fiber matrix content, and void content of the

Table 5: Volume content of fiber, matrix and void in #4 GFRP bars.

	Density of Composite (gm/cm^3)	Density of fiber (gm/cm^3)	Density of matrix (gm/cm^3)	Fiber Volume Fraction (%)	Matrix Volume Fraction (%)	Void Content (%)
Commercial Thermoset Rebars						
TS-1	2.16	2.61	1.15	69.6	29.5	0.8
TS-2	2.13	2.61	1.15	--	--	--
Thermoplastic Smooth Bars						
GF + PBT	2.06	2.62	1.31	63.9	29.5	6.6
GF + PA12	1.87	2.62	1.01	59.0	31.6	9.3
GF + PP	1.91	2.62	0.90	61.8	32.6	5.6

Table 6 shows the glass transition temperatures of the rebars used for this study and the melting temperatures of the thermoplastic bars used for this study.

Table 6: Thermal transition temperatures of #4 thermoset and thermoplastic bars.

	Glass Transition temperature T_g (°C) ± COV %	Melting temperature T_m (°C) ± COV %	Melting temperature of UD Tape (°C)
Commercial Thermoset Rebars			
TS-1	102 ± 1.13 %	---	---
TS-2	102 ± 0.83 %	---	---
Thermoplastic Smooth Bars			
GF + PBT	52.5 ± 1.6 %	223 ± 0.12 %	223
GF + PA12	46.7 ± 2.3 %	175 ± 0.46%	178
GF + PP	48.2 ± 1.9 %	162 ± 0.26 %	165

Table 7 shows the moisture content of the rebars after 24 hours of water immersion in a water bath at 50°C.

Table 7: Moisture Absorption at 24 hrs. in 50°C distilled water.

	Moisture Absorption 24 hrs. (%)	Standard Deviation (±)
Commercial Thermoset Rebars		
TS-1	0.02	0.01
TS-2	0.05	0.01
Thermoplastic Smooth Bars		
GF + PBT	0.35	0.03
GF + PA12	0.97	0.08
GF + PP	0.41	0.02

Table 8 shows the results of the tensile mechanical properties generated using tension tests.

Table 8: Tensile Properties of #4 GFRP bars.

	Ultimate Tensile Force (KN) ± COV %	**Ultimate Tensile Strength (MPa) ± COV %**	**Tensile Modulus (GPa) ± COV %**	**Ultimate Tensile Strain (%) ± COV %**
Commercial Thermoset Rebars				
TS-1	169 ± 2.5%	1310 ± 2.5%	64.9 ± 1.3%	2.10 ± 3.2%
TS-2	179 ± 1.4%	1390 ± 1.4%	64.0 ± 1.3%	2.18 ± 1.2%
Thermoplastic Smooth Bars				
GF + PBT	*>91.1 ± 5.4% **	*>706 ± 5.4% **	74.4 ± 0.9%	*>0.94 ± 6.0% **
GF + PA12	*>69.8 ± 13.5% **	*>541 ± 13.5% **	68.9 ± 0.9%	*>0.78 ± 13.2% **
GF + PP	*>37.7 ± 12.9% **	*>292 ± 12.9% **	*74.5 ± 3.6%**	*>0.38 ± 16.1% **

Figure 4 shows failed thermoset specimens from tension tests. The brooming failure is observable in the failed specimens.

Figure 4: Failed thermoset specimens from tension tests.

Figure 5 shows load-position plot generated from tensile testing of GFRP composite bars.

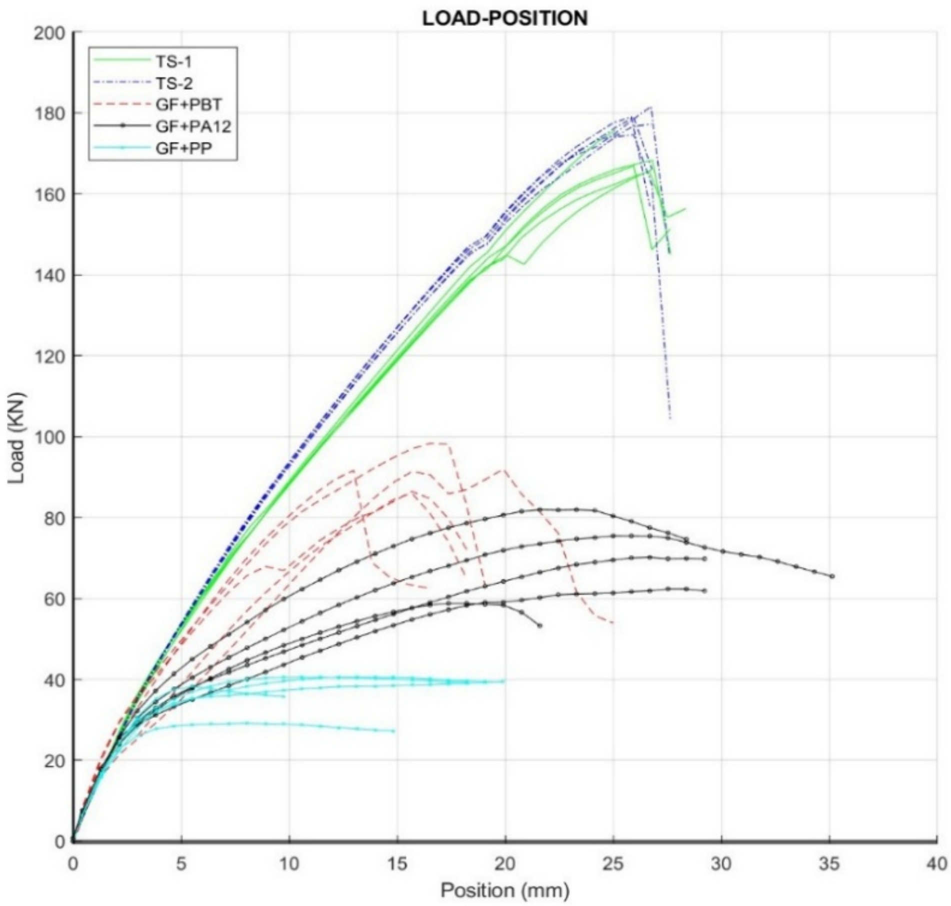

Figure 5: Load-position plot for tensile testing of GFRP composite bars.

Figure 6 shows the setup for transverse shear tests.

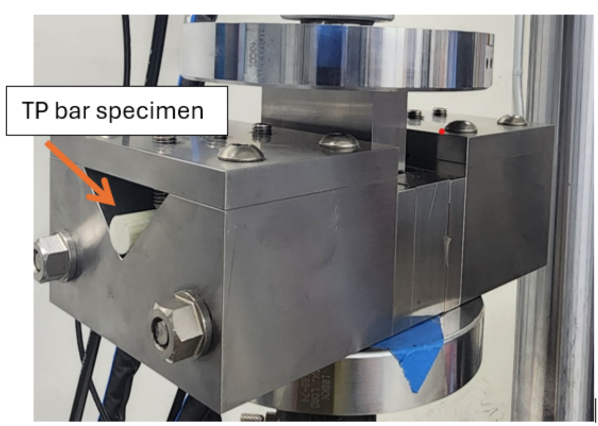

Figure 6: Transverse shear test setup.

Table 9 shows the results of the mechanical properties of the rebar specimens generated using the transverse shear test.

Table 9: Transverse shear capacity of GFRP bars.

	Transverse Shear Strength (MPa)	Coefficient of Variation (± %)
Commercial Thermoset Rebars		
TS-1	193	6.1 %
TS-2	190	3.8 %
Thermoplastic Smooth Bars		
GF + PBT	151	0.88 %
GF + PA12	115	2.3 %
GF + PP	123	1.2 %

Figure 7 shows the setup for apparent horizontal shear tests.

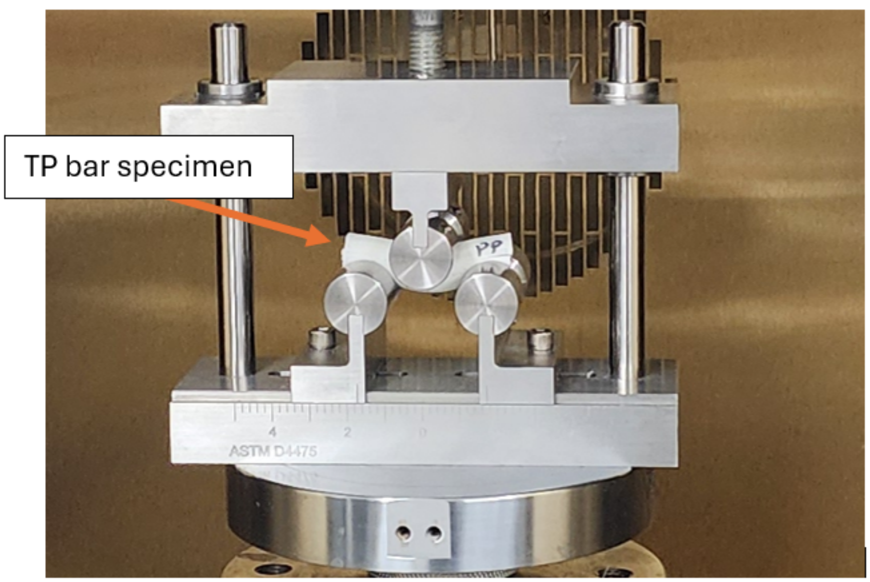

Figure 7: Apparent horizontal shear test setup.

Table 10: Apparent Horizontal Shear Strength of GFRP composite bars.

Table 10 shows the mechanical properties of the GFRP bars generated using apparent horizontal shear test.

	Peak Load (KN)	Apparent Shear Strength (MPa)	Coefficient of Variation (± %)
Commercial Thermoset Rebars			
TS-1	12.9	68.2	5.0 %
TS-2	11.3	59.4	3.3 %
Thermoplastic Smooth Bars			
GF + PBT	8.61	45.3	3.0 %
GF + PA12	4.89	25.7	6.6 %
GF + PP	4.40	23.2	8.2 %

Performance of Aged Specimen

The results from the aged specimens revealed a critical difference in durability:

- **Aged Thermoset Rebar:** The control TS rebar showed minimal to no degradation after alkaline conditioning. It retained its structural integrity and mechanical performance, confirming its well-established durability.
- **Aged Thermoplastic Rebar:** In contrast, the GF+PBT specimen did not retain its required strength. It exhibited a significant loss of mechanical properties and visible degradation of the matrix system. This poor performance was correlated with higher moisture uptake and a weaker resistance to the alkaline environment, underscoring that while the baseline properties are promising, improvements in matrix formulation are necessary for long-term durability.

Table 11 shows the tensile mechanical properties of GFRP bars after 30 days of immersion in alkaline solution.

Table 11: 30-days conditioned GFRP bar tensile properties.

Description	Nos.	Ultimate Tensile Force (KN) ± COV %	Ultimate Tensile Strength (MPa) ± COV %	Tensile Modulus (GPa) ± COV %	Ultimate Tensile Strain (%) ± COV %
TS-2 @ Base	5	179 ± 1.4%	1207 ± 1.4%	55.6 ± 1.3%	2.18 ± 1.2%
TS-2 @ Room	5	176 ± 2.4%	1188 ± 2.4%	55.0 ± 3.6%	2.22 ± 3.7%
TS-2 @ 60℃	5	177 ± 3.4%	1191 ± 2.4%	55.7 ± 3.6%	2.18 ± 2.9%
TS-2 @ 80℃	5	181 ± 2.5%	1216 ± 2.5%	56.3 ± 0.8%	2.19 ± 1.8%
GF+PBT @ Base	5	*91.1 ± 5.4%*	*706 ± 5.4%*	74.4 ± 0.9%	*0.94 ± 6.0%*

Table 12 shows the 30-day transverse shear strength of the GFRP bars after 30 days of immersion in alkaline solution.

Table 12: 30-days conditioned GFRP bar transverse shear strength.

Description	Nos.	Peak Transverse Load (KN) ± COV %	Transverse Shear Strength (MPa) ± COV %
TS-1 @ Base	5	58.1 ± 6.1%	193 ± 6.1%
TS-1 @ Room	5	55.7 ± 1.5%	186 ± 1.5%
TS-1 @ 60℃	5	56.2 ± 2.9%	187 ± 2.9%
TS-1 @ 80℃	5	54.5 ± 2.6%	181 ± 2.6%
TS-2 @ Base	5	56.5 ± 3.8%	190 ± 3.8%
TS-2 @ Room	5	56.2 ± 1.3%	189 ± 1.3%
TS-2 @ 60℃	5	54.0 ± 4.1%	182 ± 4.1%
TS-2 @ 80℃	5	54.0 ± 3.1%	182 ± 3.1%
GF+PBT @ Base	6	48.4 ± 0.88%	151 ± 0.88%
GF+PBT @ Room	5	40.6 ± 2.7%	126 ± 2.7%
GF+PBT @ 60℃	5	37.8 ± 1.6%	117 ± 1.6%
GF+PBT @ 80℃	5	38.6 ± 1.7%	120 ± 1.7%

Table 13 shows the 30-day apparent horizontal shear strength of the GFRP bars after 30 days of immersion in alkaline solution.

Table 13: 30-days conditioned GFRP bars apparent horizontal shear strength.

Description	Nos.	Peak Load (KN) ± COV %	Apparent Shear Strength (MPa) ± COV %
TS-1 @ Base	5	12.9 ± 5.0%	56.4 ± 6.6%
TS-1 @ Room	5	12.7 ± 1.5%	55.1 ± 2.7%
TS-1 @ 60℃	5	12.6 ± 3.1%	54.8 ± 4.3%
TS-1 @ 80℃	5	12.68 ± 2.2%	55.2 ± 2.6%
TS-2 @ Base	5	11.3 ± 3.3%	47.1 ± 4.3%
TS-2 @ Room	5	10.5 ± 3.0%	44.0 ± 3.8%
TS-2 @ 60℃	5	11.1 ± 4.4%	46.3 ± 3.7%
TS-2 @ 80℃	5	11.1 ± 2.5%	46.6 ± 2.1%
GF+PBT @ Base	6	8.61 ± 3.0%	35.1 ± 3.6%
GF+PBT @ Room	4	4.6 ± 3.8%	18.6 ± 4.3%
GF+PBT @ 60℃	5	3.8 ± 2.3%	15.5 ± 2.9%
GF+PBT @ 80℃	4	5.21 ± 11.6%	21.3 ± 11.8%

Conclusions and Recommendations

This research investigated the viability of novel glass-fiber reinforced thermoplastic composite rebars, manufactured using a continuous forming process, as a potential field-bendable and corrosion-proof alternative to conventional steel and commercial glass-fiber reinforced thermoset rebars. Based on the comprehensive evaluation of thermoplastic composite rebar physical, mechanical, thermal, and durability properties, the following conclusions are drawn:

1. **Acceptable Baseline Performance:** Of the materials studied (PBT, PA12, PP), the glass fiber-reinforced polybutylene terephthalate (GF+PBT) composite rebar demonstrated the most significant promise. In its un-aged (control) state, it met the baseline mechanical property requirements set by ASTM standards and performed comparably to the commercially available thermoset composite rebars.
2. **Critical Durability Deficiencies:** Durability in alkaline environments remains the most significant barrier to the immediate adoption of this material. Unlike the thermoset control rebars, which showed minimal degradation, the GF+PBT rebars exhibited a significant loss of mechanical properties and matrix degradation after accelerated aging in a high-pH solution. This deficiency was correlated with high moisture uptake of the PBT matrix system.
3. **Viable Manufacturing:** The study confirms that the Continuous Forming Machine developed at the University of Maine has potential of producing thermoplastic composite rebars with acceptable baseline properties.

This study concludes that while thermoplastic GFRP rebar, specifically GF+PBT, presents a compelling and viable concept, given its potential for field-bendability and its excellent high-temperature performance, it is not yet suitable for long-term structural applications in concrete due to deficiencies in alkaline durability.

Acknowledgements

This research project received contributions from Federal Highway Administration State Planning and Research funds as well as MaineDOT state funds. This material is based upon work supported by the Federal Highway Administration **under SPR Federal Project Number 2882200 and Contract Service Number 48113**. Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Federal Highway Administration or the Maine Department of Transportation.

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