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Managing Water in the West

Composite Materials for Reclamation Infrastructure

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This study provides a review of the current composite industry with regards to four topics areas of interest: coatings, pipelines, low-risk infrastructure, and testing of composites. The report consists of a summary report outlining the interest at Reclamation and state of the art in each of the topic areas. Recommendations are given for implementing composite materials to improve service lifetime and reduce maintenance costs of Reclamation infrastructure. Each of the topic areas is covered more fully in individual reports that are included as appendices.

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Executive Summary

Reclamation is responsible for maintaining many structures and facilities which are past their designed service life and experiencing deterioration and corrosion. As this infrastructure ages, Reclamation staff must prioritize their time to the most critical structures and components. This means corrosion inspections occur less frequently than ideal and non-critical structures are low priority for repair. In addition, new structures are being built in soils and waters that are highly corrosive. Thus, Reclamation has identified a need to expand its portfolio of materials to include a corrosion-resistant option for a variety of structures.

Composite materials offer a corrosion-resistant alternative to traditional building materials. Furthermore, they are lightweight, have generally high pressure ratings, and can be designed to provide high impact and abrasion resistance. In some applications, replacing metal and concrete components with composite materials extends inspection and maintenance cycles. The need for re-coating may be eliminated, thus saving both time and money.

At Reclamation, composite materials have not seen widespread use due to high initial costs and a history of failure with early types of composite pipe. However, advancements in technical understanding, automation of manufacture, and quality assurance and quality control processes has resulted in reduced cost and improved reliability of the products. Recent life cycle costing studies showed that many composite products for infrastructure are cost beneficial in comparison to traditional building materials, as well as less environmentally impactful.

This study provides a review of the current composite industry with regards to four topics areas of interest: coatings, pipelines, low-risk infrastructure, and testing of composites. The report consists of a summary report outlining the interest at Reclamation and state of the art in each of the topic areas. Recommendations are given for implementing composite materials to improve service lifetime and reduce maintenance costs of Reclamation infrastructure. Each of the topic areas is covered more fully in individual reports that are included as appendices.

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Introduction

Reclamation is responsible for maintaining structures and facilities in which corrosion is an ongoing problem. As existing infrastructure ages, Reclamation staff must prioritize their time to the most critical structures and components and to keeping power generation operations running efficiently. This means dewatering occurs less frequently than would be ideal for corrosion inspections and non-critical or remote structures are often a low priority for inspection or repair. In addition, new structures are being built in soils and waters that are highly corrosive, such as in water-reuse demonstration areas, where steel and concrete require additional and often expensive corrosion mitigation.

Reclamation, therefore, has identified a need to expand its portfolio of materials to include a corrosion-resistant option where steel or concrete have traditionally been used in water infrastructure. Composite materials offer corrosion resistance, in addition to being lightweight and having generally high pressure ratings and high impact and high abrasion resistance. If composite materials could replace metals and concrete in some applications, inspection and maintenance cycles may be extended and the need for costly repairs such as re-coating may be eliminated, thus saving both time and money. This study aims to review the current composite industry with regards to four topics areas of interest: coatings, pipelines, low-risk infrastructure, and testing of composites. Recommendations are offered where appropriate, for implementing composite materials to improve service lifetime and reduce maintenance costs of Reclamation infrastructure. Each of the topic areas is discussed in a stand-alone report that is summarized in this document. The full individual reports are included as appendices.

Engineered composite materials are made from two or more constituent materials that, when combined, produce a material with characteristics different from the individual components. Most composites consist of a matrix material and a reinforcing material. For example, concrete is the most widely used composite material; it is composed of a cementitious matrix with aggregate reinforcement. Engineered composites can be categorized in three general groupings according to their matrix phase: polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs). MMCs and CMCs are increasingly found in the automotive, aerospace, and bio-device industries. In the category of PMCs, fiber reinforced polymers or plastics (FRPs) are the most common composite material used in the construction industry and will be discussed extensively in this study. Opportunities for MMCs are also noted.

As mentioned above, composites benefit from the combined properties of the two constituent materials. The polymer matrix resins used in FRPs are easily manufactured into complex shapes, but their low intrinsic mechanical properties usually rule them out as structural materials. Glass, aramid, or carbon fibers have high tensile strengths along the fiber length axis, but fail in other loading conditions and are susceptible to certain types of environmental degradation. However, when the polymer matrix and fibers are combined as a composite material, the result is a high strength, high stiffness, corrosion resistant material that is lightweight and easily formed into a

variety of shapes. This makes FRP composites an attractive alternative to steel in many structural applications. Common matrix and fiber types are listed in Table I. All matrix resins listed here are thermosetting materials.

Table I. Comparison of General Properties of Composite Matrix and Fiber Materials[1]

Matrix Resins			
Name	Advantages	Disadvantages	Cost*
Epoxy	• Excellent mechanical properties • High thermal properties • High water resistance • Good chemical resistance • Long working times • Low cure shrinkage	• High cost • Proper mix ratio is critical	$$-$$$
Polyester	• Low cost • Easy to use	• Moderate mechanical properties • High cure shrinkage • Limited working time	$
Vinylester	• Very good chemical resistance • Very good mechanical properties	• High cure shrinkage • Requires high temperature post-cure to achieve mechanical strength	$$
* $ = <$4/kg, $$ = $5-10/kg, $$$ = $10-30/kg (approximate)			

Reinforcing Fibers			
Type	Advantages	Disadvantages	Cost*
Glass	• Excellent shear strength • High fire resistance • Electrically insulating • Low cost	• Low fatigue resistance • Moderate to low flexural strength	$
Carbon	• Excellent tensile strength • Excellent shear strength • Excellent flexural strength • High fatigue resistance	• Low impact strength • Low fire resistance • High electrical and thermal conductivity	$$-$$$
Aramid	• High impact strength • Low density	• Low compressive strength • Low flexural strength	$$
* $ = <$4/kg, $$ = $5-50/kg, $$$ = $50-100/kg (approximate)			

Composites are not a new class of material. As previously mentioned, concrete is a composite material and is the most ubiquitous man-made material in the world. FRPs have been used to manufacture everything from high-performance sporting equipment to the Boeing 787 Dreamliner jet. In infrastructure construction, FRPs are commonly used for pipelines, bridges, tanks, and as repair materials. A recent market forecast predicted continued growth for composites[2]. Of particular interest to Reclamation, construction and pipe and tank were the second and third largest

[1] Adapted from: GTC-5-0113, "Guide to Composites," Gurit, 2015.
[2] S. Mazumdar, "What will drive composites growth in 2015?," *Composites Manufacturing*, 2015.

market segments for composites in 2014 by volume shipped. The study predicted that the construction industry would see a boost from government funding for "retrofitting ageing infrastructure, especially bridges and roads."

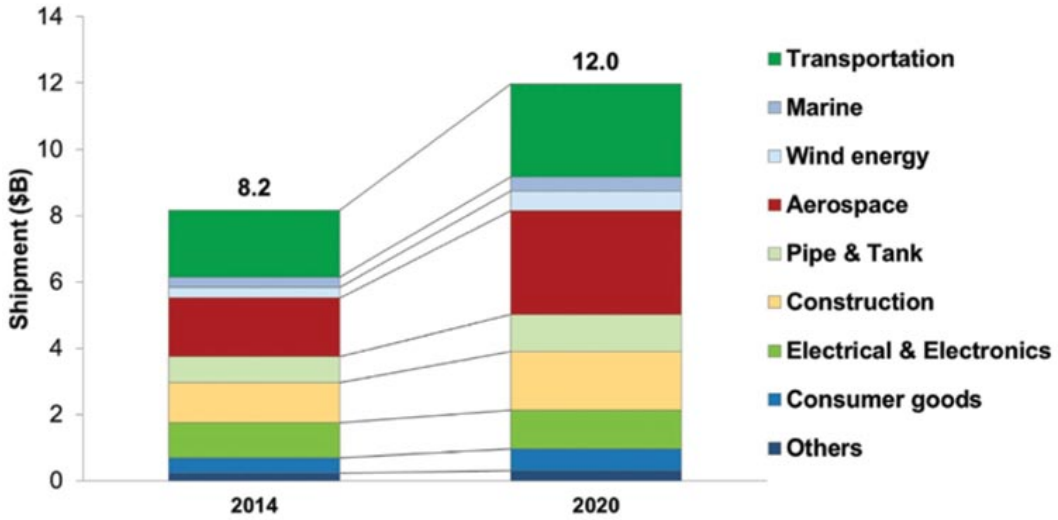


Figure 1. The US composite materials market forecast by application segment[3]

At Reclamation, composite materials have not seen widespread use due to initially high production costs from the manual nature of early industry manufacturing techniques, which led to high up-front materials costs for Reclamation clients. Additionally, a series of failures in the 1980's of reinforced plastic mortar (RPM) pipe on Reclamation projects lead to a moratorium on the materials until 1997. Advancements in technical understanding, automation of manufacture, and quality assurance and quality control processes have driven the cost of composite materials down and improved the reliability of the products. In fact, life cycle costing approaches, which include expected service life among other factors, now show many FRP products are cost beneficial in comparison to traditional building materials.[4] When environmental considerations are taken into account, composites compare well to other structural materials (Table II).[5] A study on the life cycle costs of engineered cementitious composite bridge decks showed a 37% cost savings over bridge decks made with conventional concrete over a 60-year service life.[6] Much of this savings was seen in the social cost category, which includes the much lower impact on bridge users due to fewer days under construction for the composite versus the conventional concrete. In addition, the

[3] S. Mazumdar, "What will drive composites growth in 2015?," *Composites Manufacturing*, 2015.
[4] P. Ilg, C. Hoehne and E. Guenther, "High-performance materials in infrastructure: A review of applied life cycle costing and its drivers - the case of fiber-reinforced composites," *Journal of Cleaner Production*, 2015
[5] H. Estrada, D.H. Borja, and L. Lee, "Sustainability in Infrastructure Design," in Fiber Reinforced Polymer (FRP) Composites for Infrastructure Applications, R. Jain and L. Lee (editors), 2012.
[6] G.A. Keoleian et. al., "Life-Cycle Cost Model for Evaluating the Sustainability of Bridge Decks," Proceedings of the International Workshop on Life-Cycle Cost Analysis and Design of Civil Infrastructure Systems. Cocoa Beach, Florida, 2005.

composite system consumes 40% less primary energy and produces 39% less carbon dioxide, making the reduction in environmental impact significant.

Table II. Comparison of environmental impact of structural materials[5]

Material of the bridge	Criterion: Energy consumption (MJ)	Critical volume of polluted resource
Structural steel	294,000	Water: 697.4 m^3 Air: 7,090,000 m^3
Stainless steel	329,600	Not investigated, but estimated to contribute more water and air pollution than structural steel
Composites	120,000	Water: 85.8 m^3 Air: 7,920,000 m^3
Aluminum	268,700	Water: 565.3 m^3 Air: 41,100,000 m^3
Concrete	277,200	Water: 341.9 m^3 Air: 31,040,000 m^3

The subsequent sections of this report will examine current industry practice in four areas of composite materials: coatings, pipelines, low-risk infrastructure (such as trash racks and remote irrigation gates), and testing techniques. The report will try to explain how using composites in these sectors could impact Reclamation and recommend actions for future research or implementation. In conclusion, the report will present a roadmap for the deployment of composite materials at Reclamation.

Topic 1: Composite Coatings

Composite materials for protective coatings and overlays are defined here as high performance materials applied to civil infrastructure to protect features or equipment:

> *Composite coating: liquid-applied or mastic material that cures in place and contains mechanical reinforcement*
>
> *Composite overlay: (i) a material that is constructed on location with alternating layers of resin and reinforcing fabric or (ii) a solid, prefabricated material that is placed by adhesive or mechanical fastening*

Composite coatings of interest to infrastructure applications utilize a polymer or, less frequently, metal matrix material and one or more reinforcements to improve performance in a specific service environment. These materials are marketed for improved resistance to erosion, abrasion, impact, corrosion, and cavitation when compared to traditional coatings.

Composite overlays are a broad class of products. Product types include bulk resins that are reinforced during manufacturing for easy installation by mechanical or adhesive fastening to a structure or surface. Alternately, overlays can be constructed on site by applying resin and setting the reinforcement in place. These materials can provide resistance to erosion, abrasion, impact and provide structural reinforcement.

Interest at Reclamation

Much of Reclamation's water and power infrastructure was constructed using steel and concrete materials with protective coatings, where necessary, for corrosion protection. However, a century of operation and wear warrants a search for new materials to reduce damage to structures and equipment experiencing recurring maintenance and repair challenges.

Ongoing challenges at Reclamation that could potentially be addressed using composite protective coatings and overlays include:

- Abrasion or slurry erosion damage to hydraulic equipment or structures
- Impact damage to hydraulic structures or equipment
- Cavitation damage to hydraulic equipment
- Superficial rehabilitation of concrete or steel structures
- Seismic reinforcement of structures

State of the Art

There are two types of composite coatings that are commonly used to protect civil infrastructure: polymer matrix and metal matrix. PMC coating products are either liquid or mastic materials. Most liquid products are applied through traditional methods—brush, spray, or roll—whereas mastics may require a trowel. Mastics tend to contain larger or high volume contents of pigments or reinforcements, which can be very effective at improving a material's resistance to abrasion. From a cost perspective, spray-applied liquid coatings require specialized equipment but allow for very high application rates; mastics are hand-trowel, but it is a slow and labor-intensive process. Both mastics and liquid coatings require diligent surface preparation.

MMC coatings combine a metal and, typically, a ceramic reinforcement. This class of composites is applied for thermal management applications, extreme wear or abrasion resistance, and impact and cavitation resistance. Use of these systems is somewhat limited to steel or other metallic structures that cannot be protected by less expensive methods. MMC coatings can be field applied to existing infrastructure by thermal spraying, or applied in a controlled manufacturing facility by more efficient methods such as chemical vapor deposition and electrodeposition.

Composite overlays can be used as linings, wraps, or hand lay-ups. The fiber reinforcement, typically glass or carbon, is a woven or unwoven fabric, wrap, or mat that is situated on a structure and then impregnated with a resin, such as epoxy. The most common FRP use is in steel and concrete pipeline rehabilitation and anti-seismic reinforcement of concrete structures.

Overlays can also be installed as a reinforced polymer sheet, sleeve, or shell that is prefabricated in a manufacturing facility, shipped to a project site, and bonded to the structure using compatible resin or mechanical fastening. A subset of FRP products are prefabricated as laminate overlays, while other examples utilize thermoplastic resins such as ultra-high molecular weight polyethylene. These are lower cost but less durable in immersion service.

Several organizations provide guidance for the selection, design, installation, or inspection of composite coatings and overlays, including National Sanitation Foundation (NSF)/American National Standards Institute (ANSI), American Water Works Association (AWWA), and ASTM International (ASTM) offers guidance for laboratory and field evaluation of composite materials. Composite coatings are inspected by the same methods as traditional coatings, and the American Concrete Institute (ACI) has published standards for FRP on concrete. A more comprehensive review of standards for design, installation, and inspection is included in Appendix A: Composite Coatings.

Recommendations

There are many promising applications for composite protective coatings and overlays at Reclamation, especially in the areas of impact, abrasion, and erosion resistance. These applications should be further explored with life cycle costing studies to compare composites to traditional coating materials. Performance specifications will need to be developed for each new application of composite coatings. Some specific structures recommended for composite coating or overlay implementation include: concrete spillway floors or side walls, concrete dentates, radial gate skin plates, high cavitation zones, and underwater repairs.

Topic 2: Composite Pipe

A variety of materials are used to construct water transmission pipelines including lined and coated steel, ductile iron, concrete, and plastic (polyvinylchloride and high density polyethylene). Composite materials, primarily glass fiber reinforced polymers (GRP), are also gaining market share in pipe manufacturing industry. The service requirements, such as pressure, length, capacity, and environmental conditions, determine the size and material used for the pipe. Composite pipe can be more expensive than other pipe options (concrete, steel, and plastic). However, its higher operating pressure capabilities can make it a good alternative to plastic pipe. Composite materials have a higher strength to weight ratio, meaning lighter pipe that leads to lower installation costs compared to steel and concrete. In addition, composite pipe offers superior performance in corrosive soil environments, when compared to steel pipe, without the costs for installation and maintenance of corrosion mitigation systems such as coatings and cathodic protection. Due to these advantages, composites are a useful material option, especially in high-pressure, large-diameter applications and applications requiring increased chemical resistance.

Interest at Reclamation

Reclamation is responsible for the operation and maintenance of thousands of miles of water transmission and distribution pipeline. Much of the pipeline network consists of steel pipe where corrosion is an ongoing problem that is only increasing in scale as these structures age. In most cases, Reclamation staff must prioritize their time to the most critical structures and components to keep power generation and water distribution operations running efficiently. This means that corrosion inspections and testing of corrosion mitigation systems on pipeline infrastructure occur less frequently than recommended. In addition, Reclamation is more frequently building infrastructure in highly corrosive soils, such as water reuse demonstration areas. Therefore, Reclamation has a keen interest in technology or materials that can aid in performing work in a more reliable, timely, and cost-effective manner by extending the time between inspection, repair, and replacement of infrastructure components. If composite materials could replace traditional pipe options (steel pipe and reinforced concrete pipe), inspection and maintenance cycles may be extended and the need for costly repairs such as re-coating may be eliminated, thus saving both time and money.

Composite pipe is not a new commercial product. Efficient production of small diameter fiberglass pipe was developed in the 1960's and Reclamation began investigating these materials around the same time. In 1983, a series of failures on RPM composite pipe occurred on Reclamation projects. The failures were catastrophic (pipe burst) leading to significant concerns regarding public safety on rural roads. In 1990, Reclamation placed a moratorium on all reinforced thermosetting resin pipe while the reasons for premature pipe failure were investigated.[7] Ultimately, Reclamation concluded that the hand lay-up manufacturing process was highly variable and produced pipe that was sensitive to construction impact damage.

Subsequent advances in composite pipe manufacturing technology seem to have addressed the previous concerns with RPM pipe, and the moratorium was lifted in June 1997. Modern composite pipe manufacturing is computer controlled, resulting in a more consistent product. Numerous industry standards now exist to ensure a quality product is delivered. However, composite pipe remains underutilized at Reclamation.

State of the Art

Composite pipelines are manufactured in two major material types: GRP, commonly referred to as "fiberglass," and steel reinforced polymer concrete. In addition, FRP repair materials are an effective option for repairing structural deficiencies in many types of existing pipe.

Fiberglass is the most commonly used composite pipeline material. It can achieve greater pressure capacity than plastic pipe and has better chemical resistance than steel pipe. It is typically manufactured by filament winding or centrifugal casting. The fibers are silica-based glass and the matrix is typically epoxy or polyester and may also contain sand (referred to as epoxy mortar or polyester mortar).

[7] Use of Fiberglass Pipe on Reclamation Projects, Memorandum, F.W. Cook, June 16, 1997

Steel reinforced polymer concrete uses a high strength polymer concrete mix which consists of a thermosetting binder and various fillers and aggregates. The steel reinforcement provides additional strength. This system is marketed for applications in which corrosion is a primary concern, for example in wastewater treatment infrastructure.

FRP repair materials typically consist of an epoxy matrix reinforced with carbon fiber and/or corrosion resistant fiberglass. FRP repairs can be field applied by hand lay-up or spray techniques to the exterior or interior of the pipe, depending on access.

There are existing standards governing most types of composite pipes and repairs, largely from ASTM and AWWA. GRP pipe is widely manufactured across the United States, and it is available in pipe diameters from 1 inch to 160 inches and above.

Recommendations

Composite pipe appears to be a viable option utilized by many industries, including raw water distribution. Designers should evaluate each manufacturer that offers full systems (pipe, joints, and fittings). The following points will need to be addressed if composite pipe is to be used at Reclamation:

- Select manufacturers who utilize fully automated production methods for fabrication, as opposed to hand lay-ups that can add uncertainty to the process.
- Design criteria to evaluate the joints from each manufacturer to ensure they do not become a failure locus.
- A quality assurance process should be developed and implemented to reduce the likelihood of premature failures.

Topic 3: Composites for Low Risk Infrastructure

A significant barrier to widespread implementation of composite materials for infrastructure applications has been their high initial cost. However, their overall service life cost can be lower due to less expensive installation, maintenance, and replacement costs. This can be especially true for off-the-shelf composite components that are readily available from a range of manufacturers. The report on composites for low risk infrastructure focuses on support structures where the consequences of failure would be relatively low cost and not pose significant threat to public safety. Low risk infrastructure includes manholes and vaults, structural components, gratings, safety infrastructure, and small gates and stop logs.

Interest at Reclamation

Many Reclamation structures utilize low-risk infrastructure, typically as subcomponents or support structures for larger systems or for safety purposes. Although not priority components, these structures are needed for operation of Reclamation facilities, and they can be difficult to replace, leading to significant operation and maintenance costs. Many of these structures have exceeded

their design life and require replacement or repair, which make it an opportune time to consider composites as a viable alternative to the traditional steel, wood, and concrete construction materials. Reclamation has interest in composite materials that can reliably and cost-effectively replace existing low-risk infrastructure components, while improving durability and service life.

FRP and polymer concrete composite materials have the potential for application in many Reclamation facilities, especially for structures that are particularly hard to protect from corrosion, e.g. grates, fish screens, trash racks, and trash rakes. Composites could also provide superior performance in structures that will be installed in highly corrosive environments, such as vaults or manholes in water reuse areas. Because of their excellent environmental stability, composites can also be a viable materials choice for components that have infrequent access for inspections and repairs, such as small gates or stop logs, or are providing critical safety functions and need long-term reliability with minimal maintenance, such as handrails, ladders, and walkway grating.

State of the Art

FRP and polymer concrete are the two main types of composites in the area of low risk infrastructure. Many manufacturers offer these components off-the-shelf or with custom designs, as needed. There are a variety of FRP manufacturing techniques which allow for a wide range of geometries of components. Structures such as manholes and vaults are often constructed via automated filament winding or spray techniques, or a chop-hoop method, which combines features of both. Beams, gratings, and rails are typically pultruded or molded. Polymer concrete can be used to form pre-cast components such as vaults and manholes. There are also manufacturers who offer custom design and forming for size-specific applications such as small slide gates.

As in other applications of composites, these materials provide excellent chemical resistance in a variety of environmental and service conditions, making them good candidates for structures that will be buried or immersed in highly corrosive soils or waters or will be required to contain corrosive materials. FRP and polymer concrete composites both have favorable strength-to-weight ratios as compared to steel, as low as 25% the weight of a similar steel component. They have lower thermal and electrical conductivities for applications such as manhole covers or powerplant infrastructure where low conductivity would be beneficial from a safety perspective. Most manufacturers offer additives to accommodate service requirements, such as ultraviolet light exposure (UV inhibitor), or aesthetic requirements, such as color (dye additives).

The U.S. Army Corps of Engineers has several pilot tests of composite materials completed or ongoing, including composite timbers for bridge construction and a series of composite wicket gates on the Ohio River.

Recommendations

Many low-risk infrastructure components could be installed with few changes to Reclamation performance specifications. Some examples of components that are already being produced from multiple manufacturers, some currently in use on Reclamation projects, include: gratings, guardrails, handrails, ladders, stairs, stair treads, manhole covers, and vaults. Testing procedures already exist for these components, and quality assurance testing could be adopted by Reclamation.

Other structures, such as trash racks, trash rake teeth, and remote canal gates require further investigation prior to specification on Reclamation projects. These structures are often custom-produced components, and the monetary investment is larger than for some of the off-the-shelf products listed previously. Current installations of composites at Reclamation and the Corps of Engineers should be further studied for lessons-learned. Quality assurance procedures would need to be developed for verification of delivered products.

Life cycle cost analysis should be performed versus traditional materials for each type of structure prior to wide-spread implementation.

Topic 4: Testing Composite Materials

Interest at Reclamation

As discussed in previous sections, using modern composite materials, such as FRPs, offer a viable alternative to traditional construction materials in many applications. However, the selection of a new material requires an understanding of performance under the anticipated service conditions for the expected life of the structure. Although composites have been on the market for several decades, new production methods, component designs, and intended applications are frequently introduced with little historical field data. Laboratory testing provides a way to determine estimated lifetime and performance of a new material in a simulated service environment.

A host of standards exist that are relevant to testing of composite materials. Some of these test methods are specific to composite materials, others exist to test the individual components of the composite, and still others are designed for materials such as plastics, but have been applied to composites. It is assumed that Reclamation will be designing performance criteria for any structure where composites are a viable option. The purpose of this report is to summarize available testing standards and their suitability for providing feedback on the performance and quality of composite materials that are of interest for Reclamation projects.

State of the Art

The tests presented in this report (in full as Appendix D: Testing Composite Materials) were selected primarily based on references from standard specifications as well as their common usage by composites manufacturers. The standards referenced are from organizations including ASTM, ANSI, AWWA, the International Organization for Standardization (ISO), and European Standards (EN). Several manufacturers were contacted with regard to typical and reported testing regularly employed on their products. The manufacturers were selected from the accompanying Reclamation reports on composites for coatings, low-risk infrastructure, and pipelines, and limited to those manufacturers located in the United States. Testing methods are presented in the categories of weathering, moisture absorption, ultraviolet light exposure, freeze/thaw cycling, chemical resistance, physical durability, and engineering properties. The most commonly used tests are tabulated and include the property tested, the designation, and the relevant type of infrastructure.

Recommendations

Reclamation should evaluate each new application of composite materials and determine on a case-by-case basis what tests or inspections would be required in a specification for quality assurance and acceptance of a product. Reclamation should also ensure that manufacturers have a good quality control program in place for any new composite products that come on the market.

Roadmap for Future Research

Roadmapping enables us to determine where and when future research and/or implementation efforts should be focused in order to provide the greatest benefit to Reclamation. This report examined the current state of the art for composite materials in key infrastructure topic areas. Additional research needs were identified and recommendations made for implementation of composites at Reclamation. This report provides a summary of the findings in the four individual topic reports (attached as Appendices).

Table III provides a roadmap for implementation of composites at Reclamation, including outstanding needs and notes for specific infrastructure features that have been covered by this report. Each feature in the table is capable of being implemented at Reclamation within five years.

In addition to the features addressed in the table, there are several infrastructure areas where composites could be a useful alternative to conventional materials, but the timeline to implementation is longer and more in-depth exploration is required. This includes large gates (bulkhead, radial, and slide), tanks and air chambers, and turbine runners. See the 2010 report prepared for the U.S. Army Corps of Engineers by West Virginia University for a review of the history of composite gate installations in the U.S., Japan, and Europe.[8]

[8] H.V.S. GangaRao and P.V.Vijay, "BAA Topic No. CHL-2: Inland Hydraulic Structures: Feasibility Review of FRP Materials for Structural Applications", Prepared for the U.S. Army Corps of Engineers, 2010.

Table III. Roadmap for Implementation of Composites at Reclamation

	Features	Materials	Needs for Implementation	Notes
Pipe	Pipe: diam. > 36-inch	FRP	Performance specification or train design engineers; train inspectors; QA program	Investigate various joints and fittings offered by manufacturers; compare whole lifecycle cost to conventional alternatives
	Pipe: 0-36- inch diam.	FRP		
Low-Risk Infrastructure	Manholes / Vaults	FRP or Polymer Concrete	Performance specification	Ready for immediate implementation
	Gate Guides	FRP	Performance specification	Immediate implementation ; confirm compatibility with existing infrastructure
	Fish Screens	FRP	Performance specification or train design engineers	Could be implemented immediately if impact resistance is not required
	Trash Racks / Rake Teeth	FRP	Performance specification or train design engineers	Demonstrate durability for service conditions (impact resistance)
	Small Slide Gates (remote canal gates)	FRP	Performance specification or train design engineers; train inspectors; QA program	Demonstrate durability for service conditions (impact resistance); confirm compatibility with existing structure
	Gratings, Guard Rails, and Ladders	FRP	Performance specification	Immediate implementation; light weight gratings may require fastening
	Manhole Covers	FRP	Performance specification	Immediate implementation
	Stairs and Stair Treads	FRP	Performance specification	Immediate implementation; request special UV protection, as needed
Protective Coatings and Overlays	Concrete Spillways	FRP or MMC coating	Performance specification	Investigate repair interface for long-term adhesion; investigate uplift
	Concrete Dentates	FRP or MMC coating	Performance specification	Immediate implementation; ensure adequate adhesion; compare lifecycle cost to stainless steel
	Radial Gate Skin Plate	FRP or MMC coating	Performance specification	Immediate implementation; ensure adequate corrosion protection and adhesion to structure
	Turbine Runner and Equipment in Cavitation Zones	PMC or MMC coating	Performance specification	Immediate implementation; ensure adequate corrosion protection and adhesion to structure
	General Underwater Repairs	FRP or PMC coating	Performance specification	Immediate implementation; ensure adequate corrosion protection and adhesion to structure
	Pipeline Repair	FRP	Performance specification; train inspectors	Immediate implementation; repair of minor degradation as a protective barrier
	Structural Repair and Reinforcement	FRP	Performance specification or train design engineers; train inspectors	Engineering design required

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Appendix A: Composite Coatings

RECLAMATION

Managing Water in the West

Technical Memorandum No. MERL-2015-034

Composite Materials for Protective Coatings and Overlays



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

September 2015

Mission Statements

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Materials Engineering and Research Lab Group, 86-68180

Technical Memorandum No. MERL-2015-034

Composite Materials for Protective Coatings and Linings

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Executive Summary

A review of composite protective coatings and overlays is provided. The specific material categories discussed are: polymer matrix composite coatings, metal matrix composite coatings, fiber reinforced polymer overlays, and reinforced polymer sheet or laminate overlays. The document includes definitions, intended uses, and commercial examples for each type. Applicable design standards, testing standards, and inspection guidance are also described.

The purpose of this review was to evaluate current practices and potential uses of these composite materials by Reclamation. An overview of potential benefits as well as cautions or weaknesses, when compared to current practices, is also provided. Recommendations for determining suitability for Reclamation are:

- Conduct a life cycle cost analysis comparing Reclamation's existing methods of protecting for abrasion resistance versus composite coatings, fiber reinforced polymer (FRP) repairs, and other materials within the scope of work of this document. The drivers identified by Ilg—external costs, an extended life cycle, the discount rate, and expected service life—should be included in the analysis [1]. A trained economist should participate in this work.

- Evaluate reinforced polymer sheet or laminate composites for short- and long-term structural reinforcement. Structural and other relevant engineers should participate in this work.

- Test composite protective coatings or overlays on non-critical structures. Several promising applications are:

    - Concrete spillway floors or side walls which have problem areas or zones that previously required repair due to abrasion or erosion

    - Concrete dentates which required repair due to impact damage

    - Radial gate skin plates at splash zones or similar structures where significant impact damage requires frequent coating repairs to maintain corrosion protection

    - Concrete sections of trash rack structures where significant impacts previously caused damage that required repair

    - High cavitation zones that previously required significant repair

    - Underwater repairs which are challenging to perform using traditional methods

    - Any other repairs or maintenance activities, routine or otherwise, which result in substandard or short repair lifetimes

- Conduct life cycle cost analysis for all composite protective coating and overlay applications which, based on demonstration results, seem well-suited for more widespread use.

- Develop performance specifications and laboratory testing protocols to complement field data obtained from demonstration projects, particularly for those applications that are deemed well-suited for more widespread use.

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Introduction

Composite materials for protective coatings and overlays are defined here as high performance materials applied to civil infrastructure to protect features or equipment. In some cases, the materials in this report also provide some structural reinforcement to the infrastructure. The following two definitions form the basis for the discussion in this report:

> *Composite coating: liquid-applied or mastic material that cures in place and contains mechanical reinforcement*
>
> *Composite overlay: (i) a material that is constructed on location with alternating layers of resin and reinforcing fabric or (ii) a solid, prefabricated material that is placed by adhesive or mechanical fastening*

Composite coatings utilize a polymer (inorganic or organic), ceramic, or metal matrix material and one or more reinforcement materials to improve performance in a specific service environment. This document reviews the potential applications for polymer and metal matrix composites. These materials are usually claimed to improve resistance to erosion, abrasion, impact, corrosion, or cavitation compared to traditional protective coatings.

Composite overlays are a broad class of products. Product types include prefabricated thermoplastic or thermoset (chemically cured) bulk materials that are reinforced during manufacturing for easy installation using mechanical or adhesive methods to fasten the overlay to a structure or surface. Others are constructed on site by applying resin and placing the reinforcement in the resin; this is repeated to achieve a specific number of layers. The latter is known as FRP. Composite overlays provide resistance to erosion, abrasion, or impact and can be used to provide structural reinforcement.

Overlays have more potential applications than coatings because their thickness can be much greater, allowing for more uses. They are sometimes used for repair of civil structures as well as armoring areas susceptible to physical damage.

A major advantage of composite coatings is improved adhesion to the structure, which ensures better corrosion resistance. Some composite coatings can be spray-applied while others require hand application, increasing labor costs.

Interest at Reclamation

Reclamation owns and maintains an extensive inventory of water delivery and power generation infrastructure. Much of this was designed and built using state of the art steel and concrete materials from several decades ago. Corrosion control for steel is traditionally provided by protective coatings, and the concrete structures were designed for a long service life using the best available knowledge at the time of construction. However, over a century of operation has revealed a number of problems relating to recurring maintenance and repair challenges. New materials may perform better that will reduce damage from recurring deterioration mechanisms to structures and equipment.

Composite materials can be designed to enhance specific performance properties. In fact, Reclamation has used concrete, a composite material, as a major component of much of its infrastructure. In concrete, the binding of aggregate with cement produces a composite with good compressive strength. More recently, many other composite materials have become available as candidate engineering materials.

Ongoing maintenance and repair challenges at Reclamation that could be addressed by composite protective coatings and overlays include:

- Abrasion or slurry erosion damage to hydraulic equipment and structures
- Impact damage to hydraulic structures and equipment
- Cavitation damage to hydraulic equipment
- Surface- and moderate-depth rehabilitation of concrete and steel structures
- Reinforcement of structures for seismic loads

This document reviews the state of the art for opportunities to reduce repair and maintenance costs. Composite materials have the potential to reduce these costs through increased service life and alternative, lower-cost repair procedures.

Types of Materials and Products Available

Polymer Matrix Composite Coatings

Composite coatings contain an organic or inorganic polymer matrix. These products are either liquid or mastic materials. The product type dictates the appropriate application method. Most liquid products are applied through traditional methods—brush, spray, or roll—whereas mastics may require a trowel. Coatings requiring high film build or the ability to fill gaps or bridge cracks are often called mastics and are of a putty-like consistency. For both types, reinforcement improves a material's resistance to abrasion and similar in-service wear challenges.

Common reinforcement materials for abrasion or wear resistance include glass flakes or beads, silicon carbide (SiC), aluminum oxide (Al_2O_3), and other ceramics [2, 3, 4, 5]. Figure 1 provides micrographs of an epoxy/aluminum (Al) alloy composite cross-section. The primary application for these materials is to steel, although many are approved or designed for application to concrete.

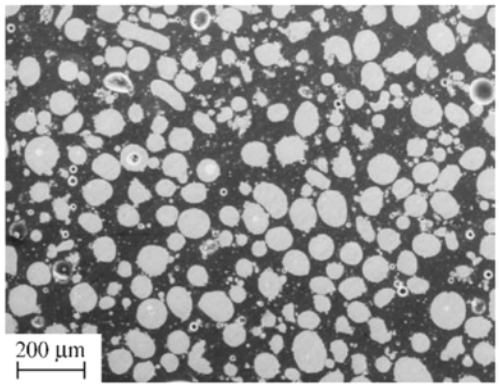


Figure 1. Example composite coating—cross-sectional micrograph of epoxy reinforced with spherical 6061 aluminum alloy particles. Reproduced from Lee, Figure 7 [5].

From a cost perspective, spray-applied coatings allow for very high application rates, on the order of hundreds of square feet per day per applicator. However, specialized equipment such as heated pots and airless sprayers are frequently required to achieve proper application. In contrast, mastics that are applied using a hand trowel can be extremely labor intensive, increasing costs correspondingly. A single applicator can apply tens of square feet per day for a thick, mastic material. Both mastics and liquid coatings require proper surface preparation. Surface preparation according to SSPC-SP10 is typical for steel [6]. If applied properly, these materials provide adhesion and corrosion resistance that is equivalent to the protection provided by traditional protective coatings. Figure 2 provides examples of current Reclamation uses.



Figure 2. Composite coatings used at Reclamation: (left) trowel-applied in a draft tube for cavitation resistance and (right) brushed onto a pump casing for sand-slurry erosion resistance.

Metal Matrix Composite Coatings

Metal matrix composites combine a metal and, typically, a ceramic reinforcement. This class of composites is largely selected for their thermal management applications [7]; however, metal matrix coatings with extreme wear or abrasion resistance are also available [8]. These materials may also have other useful properties, such as impact and cavitation resistance. Table 1 provides types of available reinforcement materials [3]. Cobalt reinforced with tungsten carbide (Co/WC) is an example of a common metal matrix composite; however, aluminum /silicon carbide (Al/SiC) may be preferred in civil engineering applications requiring lower density (lighter weight)[8].

Table 1. Typical metal matrix composite reinforcement materials. Reproduced from Chawla, Table 6. 1 [3].

TYPE	ASPECT RATIO	DIAMETER, μm	EXAMPLES
Particle	1-4	1-25	SiC, Al_2O_3, BN, B_4C
Short fiber or whisker	10-1,000	0.1-25	SiC, Al_2O_3, Al_2O_3+SiO_2, C
Continuous fiber	>1,000	3-150	SiC, Al_2O_3, C, B, W

Use of these systems is somewhat limited to steel or other metallic structures that cannot be protected by less expensive methods. Thermal spray equipment provides the opportunity to apply these materials to existing civil infrastructure equipment. Plasma spraying is one of the most advanced methods. The composite powder is fed into the plasma torch, melted, and then transferred at high efficiency and rates, making the coating of large components feasible [8]. Figure 3a shows an axial feeder which is more efficient than the alternative, radial feeder. Figure 3b provides an Al alloy/SiC composite cross-section as an example. Other application methods are available, including chemical vapor deposition and electrodeposition, but these are reserved to use in manufacturing or shop fabrication facilities.

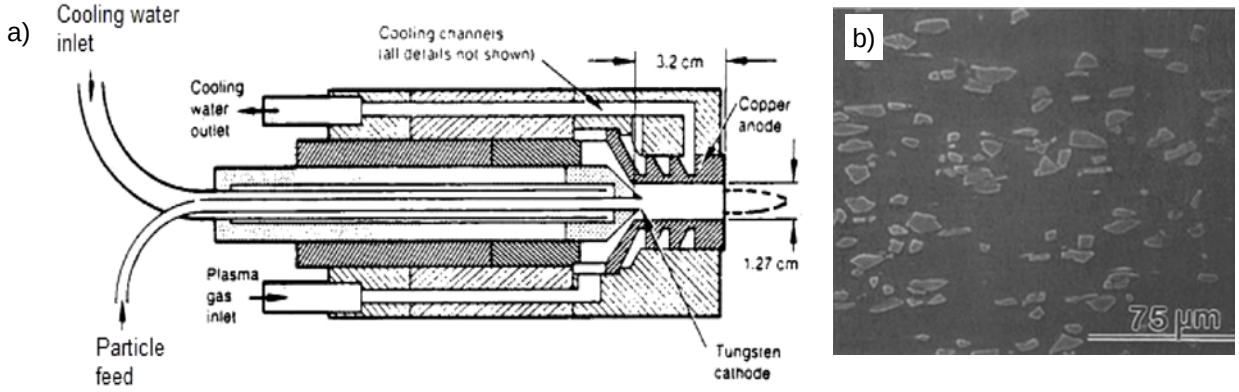


Figure 3. a) Plasma torch schematic for an axial powder feed. Reproduced from Tailor, Figure 1 [8]. b) Typical microstructure of aluminum alloy with SiC particles. Reproduced from Chawla, Figure 6.1b [3].

Fiber Reinforced Polymer Overlays

FRP composite overlays can be used as a lining, wrap, or hand lay-up. The fiber reinforcement is a woven or non-woven fabric, wrap, or mat. One example is unidirectional fabric (Figure 4), which imparts anisotropic properties to the composite system. The advantage of unidirectional fabrics is that they can be oriented in any direction during placement, providing the composite strength in many directions, e.g. layering cloths with fibers at 0 degrees, 45 degrees, and 90 degrees from horizontal.



Figure 4. Unidirectional carbon fiber fabric for FRP; fibers are oriented in the vertical direction.

Woven fabrics or cloths can have fibers oriented in multiple directions, in a single fabric, typically 0˚ and 90˚. The lengthwise reinforcement is known as warp and crosswise as fill (Figure 5a) [9]. Woven fibers are slightly out-of-plane, resulting in lower tensile strengths; additional stresses are added to the woven matrix when straightened under load [10]. Plain weaves provide excellent stiffness, whereas the satin weave is more adaptive to structure contours or features (Figure 5b) [9].

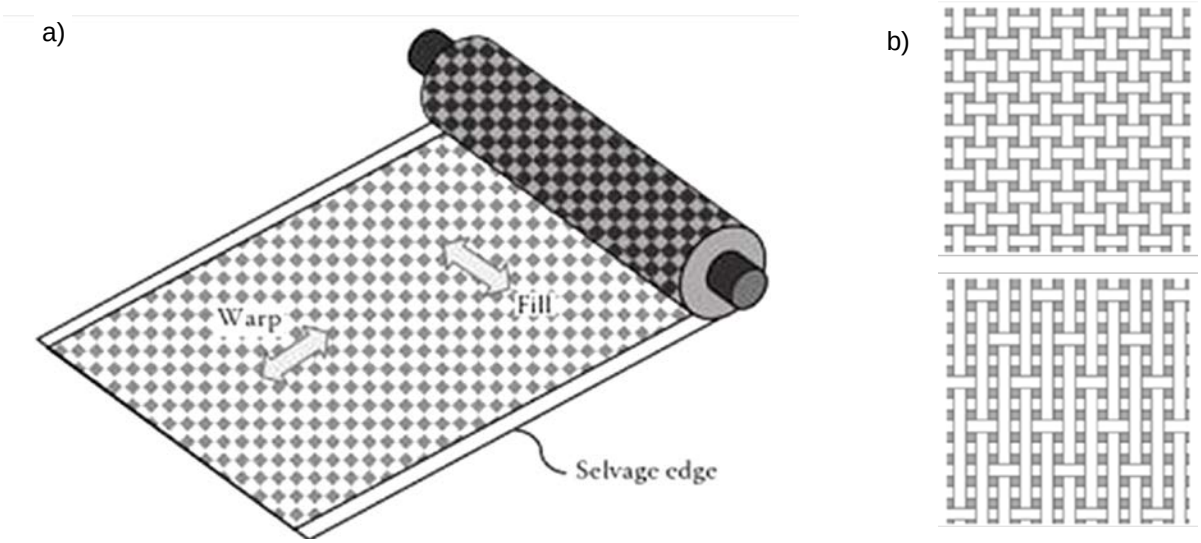


Figure 5. a) Example of woven fiber fabric with warp and fill directions shown; b) plain weave (top) and satin weave (bottom). Reproduced from Zoghi, Figures 3.12 and 3.13 [9].

One of the most common FRP uses is steel or concrete pipeline rehabilitation [9, 11, 12, 13, 14, 15]. However, seismic reinforcement of cracks in concrete gravity dams is under evaluation [16]. Table 2 provides the advantages and disadvantages for the three commonly used FRP resins. Epoxy resin is most common for pipeline rehabilitation due to its superior corrosion resistance. In terms of reinforcement, glass or carbon fibers are preferred for immersion or corrosive soil service because of their high strength and inherent corrosion resistance. These products are glass FRP (GFRP) and carbon FRP (CFRP), respectively. Figure 6 provides an example of a CFRP layup for a repair on a 15-foot inner diameter reinforced cast in place concrete pipe at Weber Coulee Siphon, Moses Lake, WA. Many FRP options are National Sanitation Foundation International (NSF) / American National Standards Institute (ANSI) 61 certified [17].

Table 2. Comparison of FRP resins. Reproduced from Shamsuddha, Figure 6 [12].

RESIN	ADVANTAGES	DISADVANTAGES
Epoxy	– Superior physical and mechanical properties – Low cure shrinkage – Better adhesion – Better compatibility with carbon fibers – Good moisture and chemical resistance	– Higher cost – May possess corrosive content and may degrade under UV
Polyester	– Low cost – Available and easily applicable	– Moderate strength – Low durability – High cure shrinkage – Low strain prior to failure – Less compatible with carbon fibers
Vinyl ester	– Better strain and strength performance than polyester – Low cost	– High shrinkage and exothermic temperature during curing – May require post curing – Lower strain and carbon compatibility than epoxy



Figure 6. FRP installation at Weber Coulee Siphon, 15-foot inner diameter reinforced cast in place concrete pipe; application of saturated carbon fiber fabric material in longitudinal direction (left) and completed CFRP lined section (right).

Prefabricated Sheet or Laminate Overlays

Overlays, as defined here, are a reinforced polymer sheet or laminate that is prefabricated in a manufacturing facility before shipment to the project site. Overlays are usually bonded to the structure or equipment using additional resin. Mechanical fastening may also be used when appropriate. Prefabricated overlays are more likely to use polyester resins reinforced with fiberglass or a similar material. The resulting products are lower cost but may also be less durable in immersion service.

There are many types of composite products within this broad category of prefabricated overlays. For example, some FRP's are prefabricated as laminate overlays. This reduces repair time because the laminate is simply adhered to the structure in the field. The disadvantage is that these laminates are restricted to their fabricated shape and may not conform to the structure's shape. Another example is the exterior sleeve for the repair and reinforcement of pipelines. Figure 7 illustrates this example for the Clock Spring® product [18]. This product is wrapped during application and is designed for pipe diameters of 4- to 56-inches. Some prefabricated composite overlays utilize thermoplastic resins such as ultra-high molecular weight polyethylene. These systems offer good fracture toughness and easy processing compared to thermosetting resins—epoxy, vinyl ester, and polyester [9]. Because of the wide variety of product types, careful consideration should be used during design for a specific application. Furthermore, these prefabricated systems offer several advantages over wet lay-up FRP for underwater repairs of steel pipeline [12].

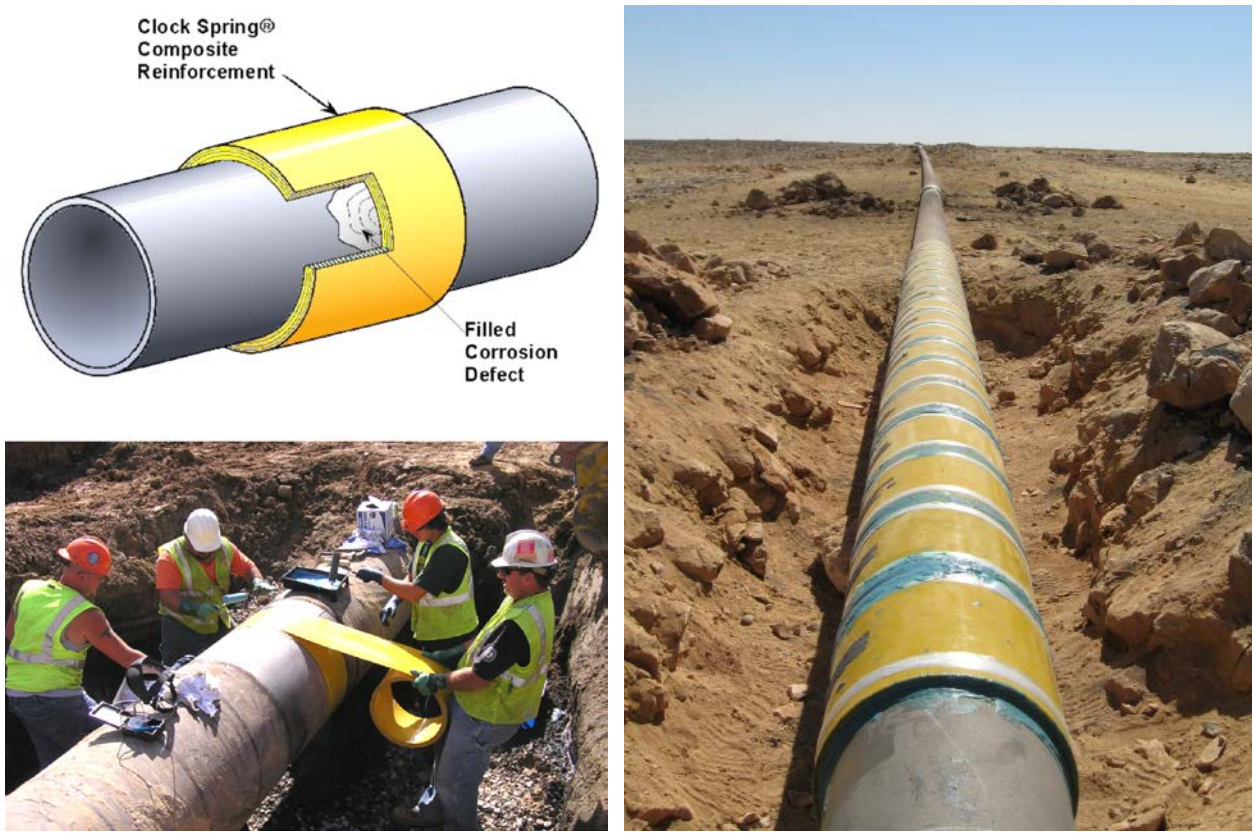


Figure 7. Clock Spring® composite repair sleeve: (upper left) illustration of sleeve and defect; (bottom left) installation; (right) completed repair. Reproduced from manufacturer data sheet [18].

Manufacturers

Table 3 provides example products for each of the composite material types described in this document. These examples were obtained from an internet search using key words: *composite coatings, abrasion resistant composite coatings, metal matrix composite coatings, fiber reinforced polymers, composite overlays*, and slight variations thereof. Many additional manufacturers and products exist that are not listed here. Product information was obtained from product data sheets on each manufacturer's website. Manufacturer technical representatives should be contacted to discuss specific application suitability prior to specifying any of these for use on Reclamation infrastructure.

Table 3. Example commercial composite coating and overlay products.

TYPE	MANUFACTURER	PRODUCT(S)	MATERIAL	POTENTIAL USES
Polymer Matrix Composite Coatings	Berry Plastics	Powercrete DD	Epoxy polymer concrete	Abrasion resistant lining
	Belzona	1000 Series Metallic Polymers	Epoxy with metal or metal alloy	Erosion and corrosion protection, metal resurfacing or lining—turbine runner, valves, pumps, pipe elbows
	3M Scotchkote	FG 512, EG 513, CR 511, EG 515, FG 514	Epoxy or polyurethane ceramic	Abrasion resistance, metal resurfacing—pumps, valves, turbine runners
	ARC Industrial Coatings	ARC 791, ARC 988, ARC NVE System	Modified epoxy or novolac vinyl ester with quartz reinforcement	Concrete repair / rebuilding down to, and including, exposed rebar or structural steel
	ARC Industrial Coatings	ARC MXC, ARC MX1, ARC I BX1	Epoxy or epoxy/urethane ceramic	Equipment in abrasion, erosion, or cavitation zones
	Metal Coatings Corp.	Ceramic epoxy coating	Ceramic epoxy coating	Abrasion resistance
	Rust Engenharia	Flakeglass Line	Glass flakes in epoxy, novolacs, etc.	Structures in total immersion or in high temperature applications
Metal Matrix Composite Coatings	Hardide Coatings	Hardide T	Tungsten carbide in metal matrix	Abrasion and erosion resistance—chemical vapor deposition of turbine runner, pumps, valves
	Deloro Stellite	Stellite 6	Carbides in cobalt alloy matrix	Wear, impact, and cavitation resistance—valve seats and gates, pump shafts
	Extreme Coatings	C5000 (CPR), C6000	Carbides with nickel, chrome, cobalt, etc.	Wear and corrosion resistance

Fiber Reinforced Polymer Overlays	Armor Plate Inc.	AP 360 Pipe Wrap	Epoxy ceramic wet lay-up fiber wrap	External pipeline coating (steel or concrete) in harsh environmental condition
	Fyfe Co. , LLC	Tyfo Fibrwrap	Carbon or glass FRP	Pipeline, column, and blast strengthening and repair—concrete and steel lining or wrap (installation by Fibrwrap Construction, Inc
	The Thortex Group	CFRP, GFRP	Carbon or glass FRP	Pipeline rehabilitation (for sale to certified applicators only)
Prefabricated Sheet or Laminate Overlays	LinkTech Inc.	Oceapoly	Polyethylene laminate with carbon fiber, fiberglass, or Kevlar	Abrasion and impact resistance
	Tega Industries	Composite Liners	High hard steel ribbed in rubber or polyurethane matrix with steel backing	Abrasion, impact, and wear resistance
	Crane Composites	AXSG	Fiberglass reinforced in polyester resin	Tank cladding—corrosion, weathering, impact, and abrasion resistance
	Fyfe Co. , LLC	Tyfo UC Laminate, Tyfo PR System	Prefabricated laminate	Reinforcing concrete or steel structures
	Clock Spring Company	Clock Spring Wrap	Fiberglass and polyester / vinyl ester resin sleeve	Repair of pipelines with corrosion damage, pits, gouges and cracks

Standards

Design Standards

Composite coatings, whether polymer or metal matrix, can be specified for Reclamation structures by making modifications for a specific application to Reclamation's existing coating specifications. FRP technology has matured to the point that design standards are available. Reclamation's FRP performance specification properties table is provided in Appendix B. Several organizations provide guidance for the selection, design, and installation of composite coatings and overlays. Specific references include:

- NSF/ANSI 61 -2013: Drinking Water System Components – Health Effects [17]
- American Water Works Association (AWWA), AWWA Manual M11-2004 Steel Pipe: A Guide for Design and Installation [19]

Many testing standards are referenced in these design standards and are available to aid in the laboratory and field evaluation of materials. ASTM International is the most widely used in the

measurement of material properties, weathering resistance, and other characteristics. Appendix A provides a partial listing of ASTM standards that may be relevant for the evaluation of composite coatings and overlays. Because most of the listed standards were developed for a component of the composite, caution must be used to properly interpret results. The exceptions are ASTM D 790, Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials [20], and ASTM D 3039, Tensile Properties of Polymer Matrix Composite Materials [21]. Modifications to any ASTM standard should be done with careful consideration and noted when reporting results.

Inspection Standards

Composite coatings are inspected by the same methods as traditional coatings. The failure modes are very similar to those of traditional materials, whether it is a polymer coating or metallizing.

The recent review by Böer [22] outlines the FRP inspection practices employed by various organizations on rehabilitated concrete structures. Several inspection standards, such as ASTM D 4541 Standard Test Method for Pull-off Strength of Coatings using Portable Adhesion Tester [23], are also included in design standards (Figure 8). For this particular destructive test, the installation of additional samples in non-critical areas during construction is recommended. Key standards for FRP on concrete include:

- American Concrete Institute, ACI 503R-93 [24]
- Intelligent Sensing for Innovative Structures Canada Research Network (ISIS Canada), Design Manual No. 3 [25]

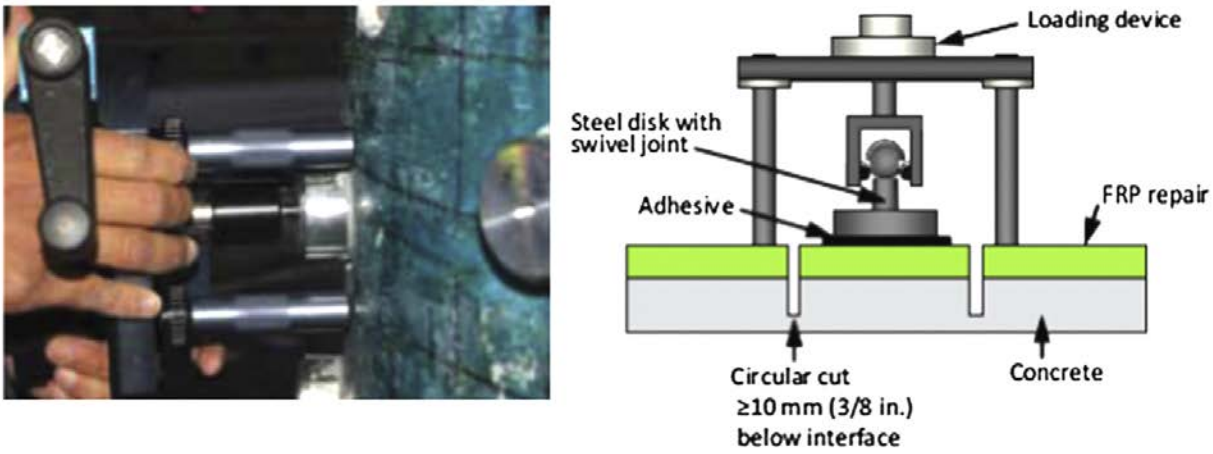


Figure 8. Destructive adhesion testing of FRP composite by ASTM D 4541. Reproduced from Böer [22].

Prefabricated sheet or laminate overlays need to be inspected carefully to ensure that disbonding or delamination has not occurred. Any signs of corrosion beneath these overlays should be further investigated.

Comparison to Current Practice

Potential Benefits

Composite coatings are far superior to traditional coatings for structures needing any combination of abrasion, erosion, impact, cavitation, or corrosion resistance. Polymer matrix composites have been applied to cavitation zones on Reclamation turbine equipment as well as pump casings. Pipelines carrying highly turbulent or sediment laden water are a good application of composite coatings because traditional coatings fall short of desired performance in these exposure conditions. Metal matrix composites should also be evaluated for use in cases where the most extreme exposures are experienced. Due to their high cost, it may be appropriate to limit their use to small areas.

FRP composite overlays have also seen limited application at Reclamation for steel or concrete pipe repair. Here, the greatest benefit of FRP compared to traditional repair practices is structural reinforcement. A proper FRP design accounts for internal and external pressures, fluid hammer pressures, and joint details to restore original function to the pipe system. FRP materials are widely available, are light weight, and easily hand carried to the application area; thus these repairs can proceed more quickly than those needing a costly and time consuming excavation. Repair materials are simply transported through manholes to the failure site, applied, and then cured for several days prior to returning the structure to service. Prefabricated overlays can also be used in this way and can further reduce application time because they are attached as a single material; hence there is no need to construct composite layers in place.

Reinforced polymer sheet or laminate overlays have the potential to serve additional, unique applications. The example of seismic reinforcement of structures is one example [16]. Further research and demonstration at Reclamation could either support broader use for this use or find limited relevance. Another example for this application is for concrete or steel structures presently receiving severe impact or abrasion damage. The composite material application can be limited to a small zone in the damage pathway. Potential structures include abraded spillway floor or sidewall sections, spillway dentates, trash rack structure supports, and radial gate skinplates at the splashzone (Figure 9).



Figure 9. Example locations for composite materials: (left) spillway dentates experiencing erosion and impact damage; dentate at lower left is missing corner and lower right is cracked and (right) gate exposed to extremely abrasive water. Photo at right reproduced [26].

Weaknesses / Cautions

The general caution in using composite protective coatings and overlays is a lack of knowledge and experience. However, researchers continue to grow the existing knowledge base for specific materials and uses in different environmental conditions. Service life and failure mode information is becoming verified through actual service in a variety of conditions.

Polymer Matrix Composite Coatings

The greatest weakness for protective coatings is always in the application quality. Ease of application is important because a contractor, who may or may not have experience with the system, is generally contracted to perform the task. Reclamation requires contractors to certify that their applicators are experienced with the materials of interest, but this quality assurance measure is at times not enough to produce the desired outcome. Maximizing the ease of application further improves the average application quality. A certified coatings inspector can also aid in ensuring that a coating material is properly applied.

Good adhesion to a steel structure is critical to provide effective, long-term corrosion protection in immersion or alternating immersion and atmospheric exposure. In addition, epoxy resin composites degrade in ultraviolet light; therefore, caution should be used when epoxy is exposed to the sun. Coating adhesion to concrete is generally poor and is negatively affected by moisture in the concrete. Repair methods for composite coatings needs more research and demonstration to determine the composite coating repairability by overcoating or using spot repairs.

Metal Matrix Composite Coatings

Metal matrix composites must be carefully selected when applied to metal to ensure there are no negative effects from the introduction of dissimilar metals. Likewise, if the system is designed to provide cathodic protection for any coatings defects that result from service, then the water chemistry must be taken into account during material selection. For example, zinc can provide corrosion protection in a wide range of water chemistries but is passivated (protection mechanism ceases) in others. Another factor to consider is that metal matrix composites are much denser, and

thus heavier, than traditional polymer matrices. Load and alignment issues should be considered early in the planning stages and reviewed by the appropriate engineer.

These composite materials are the least well-developed for infrastructure use and field-application. Therefore, many unknowns exist. Due to relatively slow material deposition rates, use will most likely be restricted to relatively small repair areas such as isolated areas of cavitation damage on turbine runners.

Fiber Reinforced Polymer Overlays

FRP composites require skilled field applicators to receive a quality product. They are susceptible to degradation by the ingress of water and ions in the same way as traditional protective coatings. Loss of tensile modulus is also a concern; the eight year immersion study by Sleeper reported a modulus decrease of 16% versus un-aged samples [27].

CFRP introduces the risk of galvanic corrosion caused by dissimilar metals—carbon and steel. It is recommended that an electrically insulating layer be applied to the substrate prior to installation of the CFRP to alleviate this risk. Cathodic protection must be designed carefully for use with FRP. For example, CFRP contains conductive reinforcement that would intercept the protective current.

Prefabricated Sheet or Laminate Overlays

Reinforced polymer sheets or laminates should be carefully considered and evaluated for each potential application. For any structural reinforcement, an appropriate engineer must review the design. Differences in thermal expansion coefficients between the substrate and the composite are one variable that must be considered for exposures in a wide range of temperatures. Another weakness is that achieving a durable adhesive bond can be a challenge; mechanical fasteners can be used in some applications. Furthermore, a protective coating is required for corrosion protection prior to overlaying on steel substrates. An additional protective topcoat may be required to provide UV resistance for the overlay.

Cost

Researchers and manufacturers are focused on minimizing the initial costs of composites' constituent materials and manufacturing techniques. However, most composites remain more expensive than traditional protective coatings from a material cost standpoint. The cost of replacing any structure is extraordinarily high. Material cost is a small fraction of these costs. The recent paper by Ilg stresses the importance of comprehensive life cycle cost evaluations and reports that FRP composite structural materials provide an 8.4% cost savings over traditional methods [1].

Composite protective coatings and overlays may offer cost saving by reducing maintenance through improved resistance to corrosion, abrasion and cavitation, resulting in a reduction of a structure's lifetime cost. As another example, the higher cost of FRP composites can sometimes be easily justified by the rapid repair and return to service possible with these materials.

Cost data is limited for the materials evaluated in this document. The data available is usually not complete and does not provide enough information adequately answer whether these materials

would be suitable for a specific application. Therefore, these materials need additional research using a lifecycle costing approach to help determine suitability.

Recommendations for Implementation

It is recommended that the most promising applications be further explored for composite protective coatings and overlays. This not only includes constructions or installations but other due diligence procedures, such life cycle costing studies. Specific recommendations for implementation are outlined below.

- Conduct a life cycle cost analysis comparing Reclamation's existing methods of protecting for abrasion resistance versus composite coatings, fiber reinforced polymer (FRP) repairs, and other materials within the scope of work of this document. The drivers identified by Ilg—external costs, an extended life cycle, the discount rate, and expected service life—should be included in the analysis [1]. A trained economist should participate in this work.

- Evaluate reinforced polymer sheet or laminate composites for short- and long-term structural reinforcement. Structural and other relevant engineers should participate in this work.

- Test composite protective coatings or overlays on non-critical structures. Several promising applications are:

    - Concrete spillway floors or side walls which have problem areas or zones that previously required repair due to abrasion or erosion

    - Concrete dentates which required repair due to impact damage

    - Radial gate skin plates at splash zones or similar structure where significant impact damage requires frequent coating repairs to maintain corrosion protection

    - Concrete sections of trash rack structures where significant impacts previously caused damage that required repair

    - High cavitation zones that previously required significant repair

    - Underwater repairs which are challenging to perform using traditional methods

    - Any other repairs or maintenance activities, routine or otherwise, which result in substandard or short repair lifetimes

- Conduct life cycle cost analysis for all composite protective coating and overlay applications which, based on demonstration results, seem well-suited for more widespread use.

- Develop performance specifications and laboratory testing protocols to complement field data obtained from demonstration projects, particularly for those applications that are deemed well-suited for more widespread use.

Project Information

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Appendix A. Testing Standards

Table 4. Partial listing of ASTM standards for evaluating composite protective coatings and overlays:

ASTM	TITLE
B117	Practice for Operating Salt Spray (Fog) Apparatus
C882	Bond Strength of Epoxy Resin System Used with Concrete by Slant Shear
D570	Water Absorption of Plastics
D610	Practice for Evaluating Degree of Rusting on Painted Steel Surfaces
D638	Tensile Properties of Plastics
D695	Compressive Properties of Rigid Plastics
D714	Test Method for Evaluating Degree of Blistering of Paints
D790	Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
D822	Practice for Filtered Open-Flame Carbon-Arc Exposures of Paint and Related Coatings
D870	Practice for Testing Water Resistance of Coatings Using Water Immersion
D1014	Practice for Conducting Exterior Exposure Tests of Paints and Coatings on Metal Substrates
D1735	Practice for Testing Water Resistance of Coatings Using Water Fog Apparatus
D2240	Rubber Property – Durometer Hardness
D2247	Practice for Testing Water Resistance of Coatings in 100 % Relative Humidity
D2794	Standard Test Method for Resistance of Organic Coatings to the Effects of Rapid Deformation (Impact)
D2803	Guide for Testing Filiform Corrosion Resistance of Organic Coatings on Metal
D3039	Tensile Properties of Polymer Matrix Composite Materials
D3418	Transition Temperatures of Polymers by Differential Scanning Calorimetry
D4141	Practice for Conducting Black Box and Solar Concentrating Exposures of Coatings
D4258	Surface Cleaning Concrete for Coating
D4541	Pull-off Strength of Coatings Using Portable Adhesion Testers
D4585	Practice for Testing Water Resistance of Coatings Using Controlled Condensation
D4587	Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings
D5894	Practice for Cyclic Salt Fog/UV Exposure of Painted Metal, (Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet)

D6695	Practice for Xenon-Arc Exposures of Paint and Related Coatings
D7087	Test Method for An Imaging Technique to Measure Rust Creepage at Scribe on Coated Test Panels Subjected to Corrosive Environments
E3	Guide for Preparation of Metallographic Specimens
G85	Practice for Modified Salt Spray (Fog) Testing
G87	Practice for Conducting Moist SO_2 Tests
G134	Standard Test Method for Erosion of Solid Materials by a Cavitating Liquid Jet

Appendix B. Fiber Reinforced Polymer Specification

Table 5. Reclamation construction specification table of performance properties for fiber reinforced polymer material, as of August 2015.

MATERIAL	PROPERTY TESTED	TEST PROCEDURE	ACCEPTABLE TEST RESULT
Carbon Fiber Fabric	Edge Curling	Visual observation when fabric is rolled out	No Curl
Saturation Resin and Adhesive	Water Absorption	ASTM D 570 (24 hours)	0.2 percent
	Compressive Yield Strength	ASTM D 695 (75 degrees F, 7-day cure)	Minimum: 10,000 psi
	Flexural Strength	ASTM D 790 (14-day cure)	Minimum: 7,600 psi
	Shore D Hardness	ASTM D 2240	Between 70 and 85
	Tensile Strength	ASTM D 638 (14-day cure)	Minimum of 10,000 psi
	Elongation	ASTM D 638 (14-day cure)	5 percent
	Toxicity	Manufacturer Data Sheet	Non-toxic, Non VOC
Epoxy/Carbon Fiber Composite	Modulus of Elasticity	ASTM D 3039	Minimum: 10,500 ksi
	Laminate Thickness	ASTM D 3039	Minimum nominal thickness: 0.035inch per layer (+/- 0.005 inches)
	Tensile Strength	ASTM D 3039	Minimum: 120 ksi
	Strain	ASTM D 3039	Minimum: 0.85 percent
	Bond Strength to Concrete Substrate	ASTM C 882 ASTM D 4541	Minimum bond strength: 600 psi while having a concrete substrate cohesive failure, matrix adhesive failure is not allowed

Epoxy top coatings: 1. Approved and compatible with the CFRP system. 2. Listed by NSF for potable water use.

Appendix B: Composite Pipelines

RECLAMATION

Managing Water in the West

Technical Memorandum No. MERL-2015-032

Composite Materials for Pipelines



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

September 2015

Mission Statements

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
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Technical Memorandum No. MERL-2015-032

Composite Materials for Pipelines

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Executive Summary

A wide variety of materials are used to construct water transmission pipelines with the most common being ductile iron, lined and coated steel pipe, concrete/reinforced concrete pipe, polyvinyl chloride (PVC) or high density polyethylene (HDPE) plastic pipe, and fiber reinforced polymer (FRP) pipe. If composite materials are used in place of some of these other pipe options (steel pipe and reinforced concrete pipe), inspection and maintenance cycles could be extended and need for costly repairs such as re-coating could be eliminated, thus saving both time and money. Reclamation began installing a type of FRP pipe called reinforced plastic mortar (RPM) pipe in 1973 until 1983 when a series of pipe failures began occurring in diameters ranging from 24 to 48 inches. The failures were catastrophic (pipe burst) leading to significant concerns regarding public safety. In 1990, Reclamation placed a moratorium on all reinforced thermosetting resin pipe while the reasons for premature pipe failure were investigated [1]. Reclamation concluded that the manufacturing process was highly variable. Subsequent advances in composite pipe manufacturing technology seem to have addressed the previous concerns with RPM pipe and the moratorium was lifted in June 1997. Modern RPM pipe is centrifugally-cast using chopped fibers. Manufacturing is computer controlled resulting in a consistent product. The centrifugal cast process results in a dense pipe wall with complete resin saturation of the glass and sand filler. Some of the old pipe remains in service, but, despite the moratorium being lifted, no pipe meeting the new American Water Works Association (AWWA) M45 “Fiberglass Pipe Design” has been installed by Reclamation. In addition, there has been no laboratory testing of the newer pipe systems at Reclamation.

While Reclamation designers had some lingering concerns, FRP pipe appears to be a viable option utilized by many industries including wholesale water distribution. Designers should evaluate each manufacturer that offers full systems (pipe, joints, and fittings). To the extent possible, it is recommended to select manufacturers who utilize fully automated production methods for fabrication, as opposed to hand lay-ups which can add uncertainty/variability to the process. In addition, it may be useful to develop design criteria to evaluate the joints from each manufacturer to ensure they do not become a failure locus. A quality assurance process should be developed and implemented to reduce the likelihood of premature failures. A quality assurance process would utilize appropriate non-destructive evaluation (NDE) techniques and hydrostatic pressure testing as a check on the manufacturer’s quality control program. Additional research has been proposed to further investigate GRP (glass reinforced polymer) pipe and address the concerns of the Reclamation design team.

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Introduction

A wide variety of materials are used to construct water transmission pipelines with the most common being ductile iron, lined and coated steel pipe, concrete/reinforced concrete pipe, plastic pipe (polyvinyl chloride (PVC) and high density polyethylene (HDPE)), and fiber reinforced polymer (FRP) pipe. In this report, FRP is a general term used to describe a material with a polymer matrix containing reinforcing fibers. The service requirements such as pressure, length, and capacity determine the size and material used for the pipe. FRP pipe is typically more expensive than other pipe options (concrete, steel, and plastic) but has higher pressure capabilities, per unit weight, and excellent chemical resistance. Therefore, FRP pipe is cost competitive in high-pressure, large-diameter applications, requiring increased chemical resistance. FRP pipe often has lower installation costs than steel or concrete pipe due to its lower weight, which can partially offset the higher material cost. In addition, composite pipe is a corrosion resistant alternative to steel pipe, offering superior performance in certain soil environments and design situations.

For steel pipe, it is necessary to coat or line the pipe surface to prevent corrosion from compromising the structural integrity of the pipe over time. Coatings have a finite service life and must be repaired or replaced periodically. Plastic pipe has lower maintenance requirements but has much lower operating pressures than steel. Composite pipe combines the strength of metallic pipe with lower maintenance requirements of plastic pipe. Numerous industry standards exist and yet the FRP pipe remains underutilized at Reclamation. The goal of this study is to provide information on composite pipeline materials and highlight any areas that are in need of additional research to facilitate increased use on Reclamation projects.

Interest at Reclamation

In addition to large dams, Reclamation is responsible for the operation and maintenance of thousands of miles of water transmission and distribution pipeline. Much of this network consists of metallic pipe where corrosion is an ongoing problem that is only increasing in scale as these pipelines age. In most cases, Reclamation staff must prioritize their time to the most critical structures and components to keep power generation operations running efficiently. This means that corrosion inspections and testing of corrosion mitigation systems on pipeline infrastructure occur less frequently than recommended. In addition, Reclamation is building infrastructure in highly corrosive soils more frequently, such as water reuse demonstration areas. Therefore, Reclamation has a keen interest in technology or materials that can aid in performing work in a more reliable, timely, and cost-effective manner by extending the time between inspection, repair, and replacement of infrastructure components. If composite materials could replace some of the traditional pipe material options (e.g. steel pipe and reinforced concrete pipe), inspection and maintenance cycles could be extended and the need for costly repairs such as re-coating could be eliminated, thus saving both time and money.

FRP pipe has been around for a long time. Efficient production of small diameter fiberglass pipe was developed in the 1960's and Reclamation began investigating these materials around the same time [2]. In 1972 and 1973, Reclamation conducted deflection testing on various flexible pipe options including steel pipe, GRP pipe (glass reinforced pipe) i.e. fiberglass pipe (a specific type of FRP), and reinforced plastic mortar (RPM) Pipe, a type of GRP pipe containing sand mixed into the resin to thicken the pipe wall to control stiffness. The deflection tests were performed in sand backfill using the Reclamation's large universal test machine [3, 4]. In 1976, a team was established to evaluate the suitability of RPM pipe for use in Reclamation construction. Among the conclusions reached by the team in their 1977 report were that the quality of pipe was dependent on operator skill and defects that still occur frequently [5].

FRP pipe is used for high pressure applications (up to 4000 pounds per square inch (psi)) and is commonly used for underground fuel piping systems in the oil and gas industry. It is estimated that 150 million miles of this fuel piping are currently installed. Reclamation installed a type of FRP pipe, RPM, pipe from 1973 until 1983, when a series of failures occurred in pipes with diameters ranging from 24 to 48 inches. At that point, there were approximately 90 miles of RPM pipe installed across 11 projects. The RPM pipe was typically buried in the right-of-way on rural roads. The failures were catastrophic (pipe burst) leading to significant concerns regarding public safety. The failures were on pipe sold under the trade name "Techite", a product developed in the late 1960's. In 1990, Reclamation placed a moratorium on all reinforced thermosetting resin pipe while the reasons for premature pipe failure were investigated [1]. Reclamation concluded that the manufacturing process was highly variable. The glass fibers were wrapped around a steel mandrel and alternated with layers of resin and sand filler. The RPM pipe was subject to manufacturing flaws because each pipe section was essentially fabricated by hand and highly dependent on the skill of the manufacturing technician. The hand lay-up process also resulted in resin voids within the pipe wall profile. These voids made the RPM pipe highly sensitive to construction impact damage – far more sensitive than other pipe options.

Subsequent advances in composite pipe manufacturing technology seem to have addressed the previous concerns with RPM pipe and the moratorium was lifted in June 1997 [1]. Modern composite pipe is centrifugally-cast using chopped fibers. Manufacturing is computer controlled resulting in a consistent product. The centrifugal casting process results in a dense pipe wall with complete resin saturation of the glass and sand filler. Glass reinforced polymer (GRP) pipe is now commonly specified for hydropower and water infrastructure applications all over the world [6, 7]. At Reclamation, some of the old RPM pipe remains in service, but, despite the moratorium being lifted, no new composite pipe meeting the new American Water Works Association (AWWA) M45 design standard for fiberglass pipe has been installed. In addition, there has been no laboratory testing of the newer composite pipe systems at Reclamation. As part of this literature review, Reclamation designers identified the following concerns related to deployment of the new pipe:

1. Long-term reliability of joints: Previous literature reviews performed at Reclamation identified concerns for joints as a potential failure point in the system.

2. Material susceptibility to chemical exposure: Reclamation pipes may be exposed to chlorinated water or located in areas with sulfate-containing soils.
3. The ability to withstand freeze-thaw damage: Freeze-thaw conditions are possible during outside storage prior to installation.
4. The ability to withstand fire damage: Pipes or siphon ends may be exposed to high heat due to a nearby brush fire or an industrial fire in the case of a hydropower penstock.
5. Fatigue behavior: Startups and shutdowns can produce transient loading effects and steady state operation can cause high cycle fatigue loading induced by vibration.
6. Material repairability: What repair procedures are available to fix a mechanically damaged pipe and what is the expected lifespan of a repaired pipe?

State of the Art for Composite Pipe

Types of Materials and Products Available

Steel Reinforced Polymer Concrete:

Steel reinforced polymer concrete uses a high strength polymer concrete mix which consists of a thermosetting binder and various fillers and aggregates. The steel reinforcement provides additional strength for loading and micro tunnel pipe applications. This system is marketed for applications in which corrosion is a primary concern. Manufacturers claim that the material is corrosion resistant and requires no coating or lining [8]. However, the steel reinforcement embedded within the material could eventually corrode as the polymer matrix degrades over time. US Composite Pipe, Inc. gives mechanical property data for the polymer concrete, but pipe design data was not available from their website at the time of this writing



Figure 1. Polymer concrete pipe reinforced with steel. Reproduced from US Composite Pipe web page.

Fiber Reinforced Polymer (FRP) repair materials:

FRP is an effective option for repairing structural deficiencies in many types of existing pipe. They have been used in the repair of prestressed concrete cylinder pipe for more than two decades [9]. Insitumain™ is a cure-in-place repair (i.e. pipe within a pipe) product designed for pipes operating at pressures up to 150 psi and up to 60 inches diameter. iPlus™ is another composite, reinforced with carbon fiber and/or corrosion resistant fiberglass and coated with polypropylene, designed to repair pipes 24 to 96 inches diameter or even non-circular cross sections. Fyfe's Tyfo® system is a carbon fiber reinforced polymer (CFRP) system designed to repair pipes 30 inches diameter and above, up to 150 degrees Fahrenheit (°F) and 410 psi operating temperature and pressure. Fyfe offers a series of pipe repair products composed of either carbon or glass fiber reinforced epoxy matrices. Figure 2 provides examples of these products.

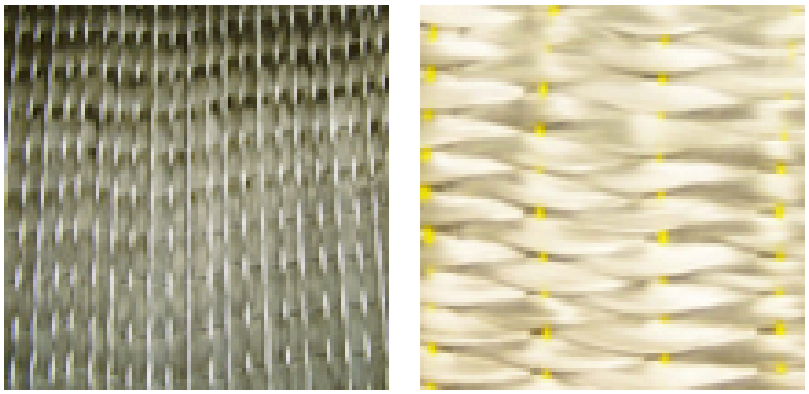


Figure 2. (left) Tyfo® SCH-41 carbon fiber reinforcing fabric and (right) Tyfo® SEH-51A glass reinforcing fabric. Reproduced from manufacturer web page [10].

Glass reinforced polymer (GRP) Pipe:

GRP (commonly referred to as "fiberglass") is the most commonly used composite pipe material. Figure 3 provides examples of large diameter fiberglass pipe. GRP pipe competes directly with lined / coated steel pipe for applications requiring greater pressure capacity than plastic pipe, such as HDPE or PVC, can achieve. It was selected for a rural water installation in north-central Wyoming based on shortcomings of the other pipe-types considered [11]. GRP pipe is typically specified and manufactured in one of two ways:

- Type I – Filament wound
- Type II – Centrifugally cast



Figure 3. Very large fiberglass pipe from Future Pipe Industries (www.futurepipe.com); (left) installed pipe sections and (right) T-connectors [12].

Additionally, hand lay-up methods may also be used by smaller manufacturers to fabricate pipe segments.

In addition, GRP may be found in several forms:

- Glass fiber reinforced thermosetting epoxy resin pipe
- Glass fiber reinforced thermosetting polyester resin pipe
- Glass fiber reinforced epoxy mortar pipe
- Glass fiber reinforced polyester mortar pipe

Current Materials and Manufacturing Practices

The reinforcing fiber is the component that gives the composite tensile strength. Fibers that have a modulus of elasticity greater than the binder (resin) strengthen the material. It is possible to use a variety of fibers in composites such as aramid (Kevlar), carbon, and glass (silica based). Organic fibers, such as hemp, have also been used but are not as strong as synthetic fibers. For economic reasons, glass remains the most widely used material for reinforcing fibers. Fibers can be either continuous or chopped. "Roving" is a bundle of glass fibers. Glass fibers are sold in an array of filament diameters usually from 9 to 23 micrometers [13]. "Tow" or "Towing" is the industry term for a group of carbon fiber filaments.

GRP pipe is constructed using one of three primary methods:

1. Hand lay-up
2. Filament winding

3. Centrifugal casting

Hand lay-up method: Fibers and resin are applied manually to a structure. The reinforcing fiber may be either woven fabric or chopped fibers. The hand lay-up method is useful for fabrication of custom parts or parts with complex geometry. In addition, capital costs are lower, making the process favorable for many smaller manufacturers. The drawback is that this method is highly dependent on the technician fabricating the pipe; therefore quality control is paramount in creating reliable a product without defects [14].

Filament winding: This process typically uses an automated process to wrap fibers around a mandrel to create the pipe. The advantage of filament winding is that the ratio of fiber to resin is higher than other methods, which gives the highest strength to weight ratio. Control of fiber orientation in conjunction with multiple layers may be used to control strength in both the circumferential direction and the axial direction [14].

Centrifugal casting: Layers of chopped glass fibers are deposited onto a tubular mold and resin and sand are added while the mold spins [14].

A GRP pipe is typically comprised of several layers. For example Flowtite® pipes are manufactured with six layers: interior layer, barrier layer, inner structural layer, core, outer structural layer, outer layer. Superlit® uses up to 11 layers to form a complete pipe [6]. Layering allows customization of the mechanical properties. For example, a layer comprised of resin-saturated chopped rovings may be added to a filament wound pipe to give additional axial strength to a filament-wound pipe.

Key Material Properties

Chemical Resistance

Polymer resins often have vastly different resistance to chemical exposure. GRP pipe can be manufactured in a dual laminated configuration with an appropriate internal liner such as fluorinated ethylene propylene (FEP), polyvinylidene fluoride (PVDF), perfluoroalkoxy alkane (PFA), polyvinyl chloride (PVC), etc. chosen for the application's service environment [15]. This gives GRP pipe the same versatility as steel pipe. Burial service in Reclamation could expose pipes to low-resistivity soils containing sulfate and/or chloride ions. Internally, pipes may be required to transport raw water with widely varying quality, treated water containing chlorine, or process water for cooling. The environment could be slightly acidic or alkaline depending on water/soil quality. Long-term service and testing has demonstrated the longevity of GRP pipe in aggressive soil environments [16]. Although it is not expected that many of Reclamation's service conditions would necessitate the selection of a specific, i.e. chemical resistant, material, designers should confirm the selected materials are appropriate for the anticipated service environment [17, 18].

Fire Resistance

Fire resistance is an important consideration for penstocks, siphons and above ground pipelines. Some manufacturers offer fire resistant resins, and the specific offerings need to be evaluated within the context of individual project needs. Ashland Chemicals manufactures fire-resistant

resins/additives for use in FRP which retard the combustion process. However the resin may still become damaged due to fire or elevated temperatures, compromising the pipe's structural integrity. Hence, it may be prudent to weigh fire resistance test data as relevant selection criteria when specifying pipe materials. The National Institute of Standards and Technology (NIST) has a fire test laboratory located in Gaithersburg, MD, which may offer capabilities to accomplish testing if no data is available.

Mechanical Durability

Mechanical durability (i.e. the ability to resist damage due to impact, abrasion, erosion, and cavitation) is an important consideration in selecting a pipe material. Limited data exists in manufacturer literature and, in the case of abrasion, there is no universally accepted test standard. Reclamation currently performs abrasion tests on coatings for steel pipe and could expand its test program to include FRP composite pipe materials.

Fatigue

Over time, repeated loading and unloading cycles can degrade fibers within the composite matrix. Some manufacturers provide an estimated fatigue life for pipe under assumed loading conditions. Generating this type of data usually requires long-term laboratory testing. A potential area for research is assessing any potential fatigue damage in the field using non-destructive test methods. The current inspection practice involves measuring dimensional changes to the pipe cross section.

UV Resistance

Many polymers, such as epoxies, experience degradation when exposed to ultraviolet (UV) light during atmospheric exposure. This can occur in service or during the storage and construction phase. Some manufacturers offer GRP composite pipe with a UV-stable superficial exterior layer. This option should be selected if long-term UV exposure is anticipated.

Design and Performance Standards

The following section provides a non-exhaustive list of industry design, performance, and testing standards that could be referenced when designing, specifying, and verifying composite materials for pipelines or pipe repair.

FRP Pipe:

American Water Works Association (AWWA)

- C950-13: Fiberglass pressure pipe: fabrication and testing standard for fiberglass pipe and joining systems.

- M45: Fiberglass pipe design (Manual of water supply practices)

National Institute of Standards and Technology (NIST)

- NBS PS 15-69–Custom contact-molded reinforced polyester chemical-resistant process equipment (obsolete, withdrawn)

American Petroleum Institute (API)

- API 15 LR – Specification for glass fiber reinforced thermosetting resin pipe

American Society for Testing and Materials (ASTM)

- ASTM D1599 – Standard Test Method for Resistance to Short Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings
- ASTM D1694 – Standard specification for threads for glass reinforced thermosetting resin pipe (Historic standard)
- ASTM D2105 – Standard Test Method for Longitudinal Tensile Properties of Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Tube
- ASTM D2992 – Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings
- ASTM D2996 - Standard Specification for Filament-Wound Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe
- ASTM D3517 – Standard Specification for "Fiberglass" Pressure Pipe. (Glass-Fiber-Reinforced Thermosetting-Resin)
- ASTM D3681 – Standard Test Method for Chemical Resistance of Fiber-glass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe in a Deflected Condition
- ASTM D4161 – Standard Specification for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe Joints Using Flexible Elastomeric Seals
- ASTM F2720 – Standard Specification for Glass Fiber Reinforced Polyethylene (PE-GF) Spiral Wound Large Diameter Pipe

National Sanitation Foundation

- NSF/ANSI 61 – 2013 – Drinking Water System Components Health Effects

American Society of Mechanical Engineers (ASME)

- ASME PCC-2-2011 – Guidance for non-metallic bonded repairs for piping

International Standards International Organization for Standardization (ISO), European Committee for Standardization (EN)

- ISO 10639 – Plastics piping systems for pressure and non-pressure water supply (GRP systems based on unsaturated polyester resin)

- EN 1796 Piping systems for water supply with or without pressure (GRP systems based on unsaturated polyester resin)

Pipe Repair:

ASTM F1216-09 Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube

ASTM F1743-08 Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe (CIPP)

AWWA Class IV - Fully structural liners; will carry the full internal pressure without support from the host pipe

Fire Resistance:

ASTM E84 –Standard Test Method for Surface Burning Characteristics of Building Materials

Installation

FRP pipe is typically installed using one of the following three methods:

1. Standard installation. The pipe is installed in a ditch with the following backfill layers: a compressed bottom layer on the bottom of the ditch if required, a compressed bed layer immediately under the pipe, a casing layer surrounding the pipe, an uncompressed upper layer except for roadway crossings.
2. Pipe jacking. This is a trenchless method for pipe installation. A tunnel boring machine is used to create the tunnel, and sections of pipe are pushed through the newly created tunnel using hydraulic jacks. This process requires good abrasion resistance on the exterior surface of the pipe and a minimum level of pipe stiffness to withstand the high jacking pressures, so the correct pipe must be chosen for this application.
3. Slip-lining refers to the process in which a new FRP pipe is installed within an existing deteriorating pipe. The external diameter of the new pipe is typically manufactured to match the interior diameter of the existing pipe, a product customization which some manufacturers provide.

Manufacturers

Table 1 provides a non-exhaustive list of manufacturers which produce GRP pipe and fittings. Other manufacturers exist including Beetle Plastics, Watani Composites, and Ershigs.

Table 1: Selected GRP Pipe Manufacturer Offerings*

Manufacturer Name	Product/ Trade name	Nominal Inner Diameter (inches)	Pressure Rating (psi)	Fiber	Resin	Notes
RPS Composites	A-Series, Dual Laminate, AA- Series, P-series, H-series	1-120	50-150	Chopped Glass	Epoxy Chemical resistant liners available	Inner and outer erosion and corrosion resistant liners are available
Superlit [6]	N/A	12-136	580	Chopped Glass (centrifugally cast)	Polyester	Automated
Superlit	N/A	12-136	580	Continuous Glass Filament	Polyester	Automated
Flowtite [7]	N/A	12-160	464	Continuous Glass Filament & Chopped Glass	Polyester, Vinyl Esters, Epoxy	Automated
Enduro [15]	Vesca	1-72	-	Continuous Glass Filament & Chopped Glass	Vinyl ester, Epoxy, Furan	Flame retardant resins available Automated or hand lay-up
ACWAPIPE	N/A	12-160	261	Continuous Glass Filament	Polyester, Vinyl Esters, Epoxy	Automated

Manufacturer Name	Product/ Trade name	Nominal Inner Diameter (inches)	Pressure Rating (psi)	Fiber	Resin	Notes
Fiberglass Systems [19]	Abrasion resistant, bondstrand, F-chem, Green thread, fiberspar, red thread HP	Depends on product	Up to 3500 psi depending on product and size	Continuous Glass Filament	Epoxy (various), Polyester	Tradenames listed for chemical and industrial applications Products also available for marine, mining, oil & gas applications
Fiberglass Systems	Centricast CL, centricast RB, Z-core	1-72	150	Chopped Glass (centrifugally cast)	Epoxy (various), Polyester	
Fiberglass Systems	Polyplaster	1-100	150	Hand lay-up, Continuous or Chop/Hoop Winding	Polyester or vinylester	
Hobas [20]	CCFRPM	18-126	250	Chopped Glass (centrifugally cast)	Polyester	Automated

* inclusion in this list does not indicate endorsement by Reclamation

Table 2 provides a non-exhaustive list of manufacturers who offer composite repair solutions for existing / aging infrastructure.

Table 2: CFRP Pipe Repair Suppliers*

Manufacturer Name	Product	Diameter (inches)	Pressure Rating (psi)	Fiber	Resin
Structural Technologies	StrongPIPE® Hybrid FRP			Carbon	Epoxy
FYFE	Tyfo® Fibrwrap® Composite systems [10]	36-201	Design dependent	Carbon	Epoxy
Insituform	Insitumain® [21]	< 36	80+	Glass	Epoxy
Insituform	iPlus® [21]	24-96	Gravity		
Enecon	Durawrap		N/A	Carbon	Epoxy

* inclusion in this list does not indicate endorsement by Reclamation

Comparison to Current Practice

Performance and Potential Design Considerations

GRP pipe and fittings are thermally stable from -50 to 50 degrees Celsius (°C) [7]. The pipes are smooth for excellent flow characteristics (Hazen-William flow coefficient (C) =150) [6, 22] and are typically designed for flow conditions from 3 to 10 feet per second. Pipe segments can be manufactured in lengths up to 50 feet. GRP pipes are approximately 25 percent (%) of the weight of steel and 10% of the weight of concrete. Superlit GRP pipes have a design life of 50 years. Some couplings carry a manufacturer estimated service lifetime of 150 years [7]. This section discusses potential issues of interest to the designer/specifier and also highlights primary differences between FRP materials and steel pipe.

Quality Control / Quality Assurance

As noted previously, Reclamation experienced a series of high profile failures of RPM pipe including most notably Lake Chelan in Washington State [23]. The early failures are believed to be related to manufacturing defects, and failed pipes predate current AWWA and ASTM standards. Catastrophic failures due to manufacturing defects may be less likely now, but a good quality assurance program should be developed at Reclamation to ensure consistency.

Surge pressure

GRP pipes are reported to be more resistant to surge pressure than steel or ductile iron, according to pipe manufacturers Superlit® and Flowtite®. This may allow for a higher factor of safety or lower weight pipe in situations where surge pressure governs pipe design.

Pipe stiffness

Stiffness refers to the vertical deflection of the pipe under an applied load per unit length of pipe and is expressed in units of psi. GRP is routinely designed to adhere to certain stiffness classes (SN), such as 18, 36, 46, and 72 psi (per AWWA C950), although some manufacturers offer a stiffness range from 9 to 144 psi. Pipe stiffness is an important consideration for the design of thin-walled pipe (flexible pipe) intended for burial service; a pipe with relatively low stiffness will flex and redistribute some of the load to the surrounding fill. Therefore, thin-walled flexible pipes, such as GRP pipe, require careful backfill control to limit deflection. Proper selection depends on factors such as the soil type (granular vs cohesive) and level of compaction. In contrast, rigid pipe (such as concrete) does not rely on the backfill to help carry the load and are, therefore, much less sensitive to backfill conditions.

Joints & Fittings

Coupling type is an important consideration for FRP composite piping. Typically, manufacturers produce pipe segments with lengths up to 50 feet. Customized longer segments may be ordered. Steel pipe is normally field welded during installation, but FRP pipes require specialized mechanical couplings to join segments together. Most manufacturers offer a full suite of joints and fittings designed to work with their pipe. Many of the couplings are unrestrained and are not, by definition, designed to carry an axial load, so this must be taken into account in the pipeline design. Bell and spigot joints with adhesive, instead of gaskets, will transfer axial loads, but manufacturer's technical literature should be consulted during design. Joints are potentially an area of concern due to the variation in type offered by individual manufacturers. However, some

manufacturers (such as Flowtite) optimistically estimate a service life of 150 years for their couplings, even though the pipe itself only has a design life of 50 years.



Figure 4: Coupling illustration- gaskets are in black. Reproduced from [6]

Flexible steel couplings are used to connect GRP pipe to other materials/pipe segments with matching outside diameters. Examples of these couplings include flexible mechanical joints, dual bolt mechanical couplings and laminated joints.

Fittings include elbows, wyes, tees, eccentric and concentric reducers, flanges and saddles. Fittings are fabricated with the same materials as pipe and are available from pipe manufacturers. ASTM D4161, EN 1119 and ISO 8639 are qualification tests which call for hydrostatic testing of GRP joints at two times the design pressure.

Repairability

All types of pipe can experience mechanical damage in service. For example, the 12-foot inner diameter aboveground steel discharge tube on Unit P-1 at John W. Keys III pumping plant was severely damaged during a rock fall incident. For repairs, the damaged area of steel pipe was cut out and a large repair patch was welded in place. For GRP pipe, different repair methods are required. Instead of cutting and welding, a section, inclusive of the damaged area, is removed, and a new piece matching the pipe wall with beveled edges is adhered in place. An FRP wrap is then applied around the pipe exterior. Manufacturers should be consulted for individual repair instructions specific to their products. The ability to perform repairs will ultimately depend on the defect size and severity.

Inspection

According to Reclamation's Facilities Instructions, Standards & Techniques (FIST) manual section 2-8, Reclamation must perform periodic inspections of pressurized steel penstocks using ultrasonic thickness testing to ensure there is adequate remaining wall thickness [24]. Wall thickness is monitored because exterior corrosion can consume metal and compromise the structural integrity of the pipe. For a non-metallic composite pipe, electrochemical corrosion is no longer a concern. However, structural integrity of the pipe could be compromised if fibers are damaged by mechanical or chemical attack. Ultrasonic thickness testing may not be feasible for pipe manufactured using laminate or layer construction, since it is difficult to accurately gauge

thickness through multiple layers with differing sound velocities. Also, fiber damage or fiber-matrix disbondment may occur without a loss in wall thickness or visible damage to the interior lining. Other manufacturing defects to test for include localized resin deficiencies, unbonded areas, and porosity. Advanced ultrasonic techniques are available to evaluate composites predominantly in a manufacturing environment [25]. Other techniques which may be applicable include radiography, thermography, and microwave [26] and acoustic emission (Figure 5).



Figure 5. NDE devices for inspecting composite materials: (left) acoustic and (right) thermal. Reproduced from [12].

Inspection of in-service GRP pipe is more complicated than steel and will require advanced techniques which are specifically suited to the pipe material and construction. However, once the pipe is successfully commissioned with stringent quality control procedures inclusive of non-destructive evaluation (NDE) techniques during the manufacturing process, performance during operation has reportedly been satisfactory, with defects being attributed to poor design or installation and not material degradation [27]. The recent review by Boer provides a state of the art on FRP inspection [28]. The Norwegian Oil and Gas Association also published guidelines for non-destructive testing of GRP pipe [27]. Reclamation does not currently have guidelines for inspection of composite pipe.

Cost

The strength to weight ratio is favorable for GRP pipe in comparison to steel pipe, potentially reducing installation costs. Depending on the diameter and pressure class, GRP pipe can be cost competitive with lined steel pipe and reinforced concrete pipe when installation costs, coatings, and cathodic protection are included. Reclamation has limited experience with specifying composite materials. Recent projects include an appraisal level study for Navajo Gallup Water Supply Project Reach 22B and the East Low Canal Siphon (156-inch diameter), where GRP was specified as an option. Table 3 provides example costs per linear foot for each pipe diameter from an undisclosed vendor.

Table 3: Sample material quote for GRP pipe [vendor undisclosed]

Diameter (in)	Price ($/ft) by Pressure Class (psi)						
	100 [psi]	150 [psi]	200 [psi]	250 [psi]	275 [psi]	350 [psi]	450 [psi]
42	$ 116.80	$ 118.10	$ 121.60	$ 126.20	$ 117.70	$ 125.30	$ 143.80
45	$ 136.70	$ 138.30	$ 142.90	$ 148.40	$ 133.10	$ 141.90	$ 163.40
48	$ 136.70	$ 138.30	$ 142.90	$ 148.40	$ 133.10	$ 141.90	$ 163.40
50	$ 155.80	$157.10	$ 159.20	$ 165.60	$ 164.60	$ 184.80	$ 212.00
52	$ 155.80	$157.10	$ 159.20	$ 165.60	$ 164.60	$ 184.80	$ 212.00
54	$ 176.10	$ 177.90	$ 183.50	$ 191.80	$ 180.20	$ 191.90	$ 220.60
56	$ 176.10	$ 177.90	$ 183.50	$ 191.80	$ 180.20	$ 191.90	$ 220.60
60	$ 192.80	$ 194.90	$ 201.40	$ 211.20	$ 198.70	$ 211.90	$ 244.70

Recommendations for Implementation

GRP pipe appears to be a viable option utilized by many industries, including raw and treated water. Designers should evaluate each manufacturer that offers full systems (pipe, joints, and fittings). To the extent possible, manufacturers should be selected that utilize fully automated production methods for fabrication, as opposed to hand lay-ups which can add uncertainty to the process. In addition, it may be useful to develop design criteria to evaluate the joints from each manufacturer to ensure they do not become a failure locus. A quality assurance process should be developed and implemented to reduce the likelihood of premature failures. A quality assurance process would utilize appropriate NDE techniques and hydrostatic pressure testing as a check on the manufacturer's quality control program.

Opportunities for Additional Research

There is significant opportunity to investigate the current GRP composite pipe products via in-house testing in the above-mentioned challenge areas. In addition, quality assurance procedures will need to be developed to evaluate as-received pipe in the field. This research could make available an economically competitive class of pipe with superior corrosion resistance that is currently not considered for Reclamation projects.

CFRP for Small Repairs on Steel Pipe

Repairs of traditional pipe materials (steel and concrete) can be performed using a woven CFRP fabric to wrap the interior or exterior of the pipe. The fabric is saturated with resin, and multiple layers may be required to achieve the desired repair strength. Typically, a repair encompasses the entire pipe circumference and is chosen for very large repairs. For smaller repairs, such as isolated corrosion damage on steel pipe due to pitting, the pit is ground, welded and the coating is then spot repaired. This process is time consuming and requires a hot work permit due to safety concerns. A more economical method may be to apply a CFRP patch to the repair area on the inner diameter

of the pipe, which would reduce the labor costs compared to that of traditional coating spot repair. The repair material could be chopped carbon fibers encapsulated in a 100% solid epoxy matrix.

This repair procedure would need to be developed and tested to ensure that full structural capabilities are restored. Variables, such as contact surface area between the repair material and the pipe, fiber loading, and length and diameter of the fibers, should be examined. One research approach would be to create defects of varying severity inside 3-inch diameter pipes, apply the CFRP spot repairs by several methods, and then use hydrostatic testing to evaluate the effectiveness of the various repairs. This type of repair method could also be evaluated for the repair of GRP pipe. Since carbon is conductive and noble to steel in the galvanic series, it may cause galvanic corrosion of the steel substrate; a dielectric insulator maybe required between the substrate and the repair. Hence, aramid and glass fibers should also be evaluated.

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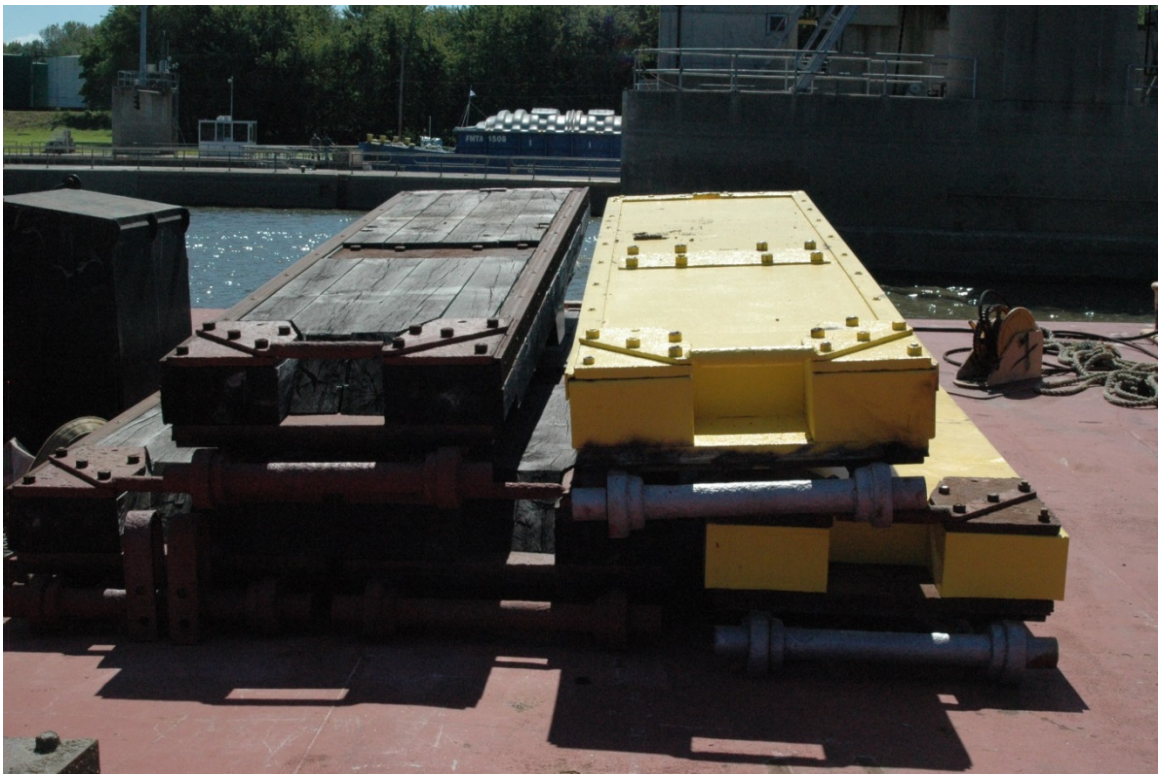
Appendix C: Composites for Low Risk Infrastructure

RECLAMATION

Managing Water in the West

Technical Memorandum No. MERL-2015-035

Composite Materials for Low Risk Infrastructure



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

September 2015

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REVISIONS

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Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ACMA	American Composite Manufacturers Association
ADA	Americans with Disabilities Act, Standards for Accessible Design
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ASTM	ASTM International
AWWA	American Water Works Association
OSHA	Occupational Safety and Health Administration
EN	European Standard
FRP	Fiber reinforced polymer. A general term which refers to a polymer composite using either glass or carbon fiber reinforcing materials. Common polymer resins are polyester, vinyl ester, and epoxy.
USACE	United States Army Corps of Engineers

Abbreviations

cw	cross-wise tensile strength of FRP
OPC	Ordinary Portland Cement
R_c	Compressive Strength
R_g	Bending Tensile Strength
R_r	Splitting Tensile Strength
UV	Ultraviolet

Units of Measure

°F	degrees Fahrenheit
°C	degrees Celsius
%	percent
hr	hour
in	inch
in^2	square inch
in^3	cubic inch
ft	feet
ft^2	square feet
m	meter
cm	centimeter – 10^{-1} m
mm	millimeter – 10^{-3} m
mm^2	square millimeter
wt	weight
g	gram
kg	kilograms (
cc	cubic centimeter
psi, lb/in^2	pounds per square inch
lbs	pounds
lb/ft^2	pounds per square foot
ksi	10^3 psi
msi	10^6 psi
MPa	Megapascal (pressure 1 MPa = 145 psi)
N	Newton (the force needed to accelerate one kilogram of mass at the rate of one meter per second squared)
btu	British thermal unit (amount of work required to raise the temperature of one pound of water by one °F)

Executive Summary

Reclamation has a significant volume of “low-risk” support structures, meaning that the consequences of failure would be relatively low cost and not pose significant threat to public safety. However, these structures are needed for operation of Reclamation facilities, and they can be difficult to replace, leading to significant operation and maintenance costs. Such low-risk infrastructure at Reclamation includes manholes, manhole covers, vaults, gate guides, fish screens, trash racks, trash rack rake teeth, small gates, grates, handrails, ladders and other similar structures. Many of these components are now failing due to long time-in-service and environmental deterioration and need to be replaced. This report examines the viability of composites as a material option for low-risk infrastructure.

A significant barrier to widespread implementation of composite materials for infrastructure applications has been their high initial cost. However, their overall service life cost is often less expensive due to lower installation, maintenance, and replacement costs. The ability for composites to be designed for specific conditions and applications ensures maximum efficiency and service life of many structures made from composites. Fiber-reinforced polymer (FRP) and polymer concrete composite materials have the potential for application in many Reclamation projects, especially in areas where structures are exposed to highly corrosive environments, e.g. grates, fish screens, trash racks, and manholes. These materials are also advantageous because of their high strength-to-weight ratio, superior chemical resistance, and flexibility in design. Additionally, FRP composites have high fatigue resistance and are thus less likely to fail when compared to metals under similar loads [1], a useful characteristic for structures such as gates and trash racks. Because of these beneficial properties listed above, structures made of FRP composite materials often have an extended service life with less required maintenance than traditional materials, such as metal or wood.

Although many composite structures have been in service for over half a century and show little sign of aging, there is a need for more research regarding suitable applications of composite materials for Reclamation infrastructure and the lifespan of different composite materials in varied environmental and service conditions. Although some accelerated testing has been conducted, there is uncertainty about how results generated from tests conducted in simulated environments predict performance in real exposure conditions for Reclamation specific applications.

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Introduction

A composite is defined as a heterogeneous material made from a combination of two or more materials differing in form on a macro scale, which when combined, retain their identities and have a unique set of properties [2,3]. These properties are largely dependent on the individual properties of the materials combined to form the composite, and the synergy between these components creates a new material (composite) with superior performance. Thus, composite materials can be designed to have outstanding performance in a specific service environment by choosing component materials that may not be sufficient alone, but when combined, produce a "best of both worlds" material. Despite the potential benefits, a significant barrier to widespread implementation of composite materials for infrastructure applications has been their high initial cost. However, their overall service life cost is often less expensive due to lower installation, maintenance, and replacement costs.

Composite materials have many properties, including corrosion-resistance, high strength-to-weight ratio, and high fatigue resistance which make them advantageous for use in low-risk infrastructure applications. For the purposes of this report, "low-risk infrastructure" includes support structures where the consequences of failure would be relatively low cost and not pose significant threat to public safety. However, these structures are needed for operation of Reclamation facilities, and they can be difficult to replace, leading to significant operation and maintenance costs. Low-risk infrastructure at Reclamation includes manholes, manhole covers, vaults, gate guides, fish screens, trash racks, trash rack rake teeth, small gates, grates, handrails, ladders and other similar structures. Historically, these structures were built with metal and wood members. Many of these components are now failing at Reclamation facilities due to long time-in-service and environmental deterioration and need to be replaced. This report examines the viability of composites as a material option for low-risk infrastructure.

In addition to flexible design possibilities, composites are easy to install in the field, because they are lightweight and can be made as a single structure. Most of these structures do not require field welding to connect the various components. Fiber-reinforced polymer (FRP) composites have seen broad usage for infrastructure applications. These materials are used both in repair and reinforcement of current installations, as well as in the construction of new structures. Popular use of these materials include highway structures, bridge decks, signposts, guardrail systems, sound barrier systems, marine piling, seawalls, grating, tunneling, culverts, drain pipes, and many more. Another composite of interest for low-risk infrastructure is polymer concrete. Polymer concrete may be used for new construction or repairing of both old conventional cement-based concrete and polymer concrete. In some limited applications, it can serve as a repair material for concrete and other materials. However, when used as a stand-alone component, such as vaults, manholes, and manhole covers, due to the difficulty of forming and quality control in the field, this material is best used as a precast component.

Reclamation has a need for materials that perform well in harsh service environments. Composites can achieve structural performance similar to or better than metal and wood for many applications,

and, unlike metal and wood, they can also resist many types of harsh environments. At Reclamation, materials can be exposed to wetting and drying cycles, freeze-thaw cycles, corrosive environments, and/or salt exposure environments. Composites are made to perform well in all of these. One disadvantage of FRP composites is their susceptibility to degradation by ultraviolet (UV) light, which occurs in normal sunlight exposure. However, inhibitors can be added to some resin composites to improve their performance under UV light exposure.

Interest at Reclamation

All Reclamation structures utilize low-risk infrastructure, typically as subcomponents or support structures for critical systems or safety purposes. Across Reclamation, many of these structures have exceeded their design life and require replacement or repair, which make it an opportune time to consider composites as a viable, possibly superior, alternative to the traditional metal and wood. Reclamation has interest in composite materials that can reliably and cost-effectively replace existing low-risk infrastructure components, while improving durability and service life.

FRP and polymer concrete composite materials have low-risk infrastructure applications, including manholes, manhole covers, vaults, gate guides, fish screens, trash racks, trash rack rake teeth, small gates, grates, handrails, ladders and other similar structures. In these structures, composites can be used because of their high compressive strength and high resistance to many environmental exposures. Although continued development and focused research into component materials and manufacturing techniques has lowered costs, initial composite costs are typically higher than those of traditional materials. However, because of their expected long lifetime and limited maintenance and repair requirements, the service life cost of these materials in many cases can be lower than for traditional materials. Reclamation should consider these life cycle costs on a case-by-case basis when considering composite materials for a project.

A general comparison of FRP and steel showing how the materials rate for various properties is shown in Table I. This table also rates the advantages of using FRP composites in lieu of steel.

Table I. Merit comparison and ratings for fiber reinforced materials and steel. [4]

Property (Parameter)	Merit/Advantage (Rating)		Rating Scale
	FRP	**Steel**	
Strength/Stiffness	4 – 5	4	1: Very Low
Weight	5	2	
Corrosion resistance / Environmental Durability	4 – 5	3	2: Low
Ease of field construction	5	3 – 4	3: Medium
Ease of repair	4 – 5	3 – 5	
Fire	3 – 5	4	4: High
Transportation / Handling	5	3	
Toughness	4	4	5: Very High
Acceptance	2 – 3	5	
Maintenance	5	3	

Note: Higher rating indicates better desirability of the property

State of the Art

Types of Materials

Fiber-Reinforced Polymer Composites (FRP)

FRP composites are readily available for gratings, guardrails, handrails, ladders, stairs, stair treads, manhole covers, trench covers, work platforms and common structural shapes, such as I-beams, rods, and tubes, as well as endless custom applications. All of these available products could be used as replacement components for current Reclamation infrastructure. Many of these off-the-shelf commercial products have options for customization of specific attributes as needed for a given service condition, such as additives to improve corrosion resistance.

One of the primary fibers used in FRP materials is glass. Other materials, such as carbon or aramid fibers, are also common but more expensive. Glass fiber-reinforced polymer, often referred to as fiberglass, consists of a polymer resin matrix reinforced by embedded glass fibers. The strength of a fiberglass structure is determined primarily by the type, orientation, quantity, and location of the glass fibers within the structure. The type of reinforcement has a significant effect on the mechanical performance of the composite, as shown in Figure 1. Typical matrix polymers for FRP with glass fibers include epoxy, vinyl ester, methyl methacrylate, polyester and phenolics [5]. Secondary fillers or additives may be used to enhance properties such as fire retardancy, flexural modulus, surface finish, and UV resistance [5].

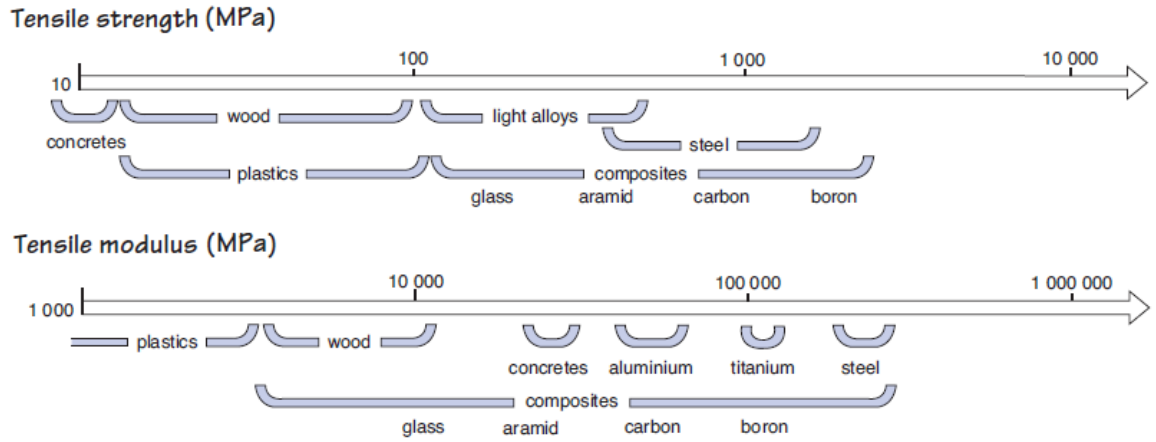


Figure 1. Tensile strength and modulus of composites in comparison to other materials [6].

FRP structures weigh approximately 80% less than steel and 30% less than aluminum. This results in lower transportation costs, easier installation, and less load to support [7]. FRP materials also have high fatigue resistance and are thus less likely to fail compared to metals under similar cyclic loads [1]. It has been shown that, for stresses below the matrix microcrack threshold, FRP components can endure over a million loading cycles [8]. A comparison between characteristics of pultruded fiberglass structures and A36 steel is provided in Table II.

Table II. Comparison of EXTREN® fiberglass structural shapes and A36 steel [9].

Compare	Fiberglass Structural Shapes	Steel A36 Carbon
Corrosion Resistance	• Available in either polyester or vinyl ester resin for resistance to a broad range of chemicals. • Painting may be necessary when exposed to direct sunlight to prevent color fading.	• Subject to oxidation and corrosion. • Requires painting or galvanizing for many applications.
Weight	• Lightweight – weighs 25% as much as steel. • ½" thick plate = 4.7 lbs/ft^2	• Could require lifting equipment to move and place. • ½" thick plate = 20.4 lbs/ft^2
Conductivity	• Low electrical conductivity properties – high dielectric capability. • Thermal conductivity 4 (btu/sf/hr/°F/in)	• Conducts electricity. Potential shock hazard. • Thermal conductivity 260-460 (btu/sf/hr/°F/in)
Strength	• High strength-to-weight ratio and pound-for-pound is stronger than steel in the lengthwise direction. • Tensile Strength = 30 ksi, cw = 7 ksi	• Homogeneous material. • Tensile Strength = 60 ksi • Yield Strength = 36 ksi
Stiffness	• Modulus of Elasticity = 2.5 msi • Will not permanently deform under working load.	• Flexural Modulus = 29 ksi • Modulus of Elasticity = 29 msi
Impact Resistance	• Glass mat distributes impact load to prevent surface damage. Will not permanently deform under impact.	• Can permanently deform under impact.
Versatility	• Pigments added to the resin provide color throughout the part. Special colors available.	• Must be painted for color. To maintain color and corrosion resistance, repainting may be required.
Easy Field Fabrication	• Can be field fabricated using simple carpenter tools with carbide or diamond tip blades. • Lightweight for easier erection and installation.	• Often requires welding and cutting torches. Heavier material requires special handling equipment to erect and install.
Cost	• Lower installation and maintenance costs in industrial applications often equal lower lifecycle costs.	• Lower initial cost.

The following paragraphs provide information on FRP usage in specific low-risk infrastructure components.

Manholes and Vaults

FRP composites for manholes and vaults are a lightweight and durable alternative to concrete with the benefit of superior performance in high-sulfate and other corrosive soils [10,11]. This is due to their lack of a cementitious phase, which can be attacked by sulfates, and the dense, hydrophobic nature of the polymer matrix, which prevents moisture penetration and corrosion of steel reinforcement. Compared to pre-cast concrete manholes, the FRP manholes are only a fraction of the weight, making them easier to transport and install [12,13]. FRP manholes are primarily manufactured by filament winding, hand lay-up, spray-up, and chop-hoop winding. Figure 2 shows two examples of fiberglass manholes. The one-piece design eliminates leakage and infiltration.



Figure 2. Fiberglass manholes constructed using chop-hoop winding method [13].

Continuous filament winding involves automated winding of a fiber around a rotating mold or mandrel while simultaneously impregnating the fibers with resin. By controlling the angle of the fibers during winding, the strength properties of the final product can be customized. Once the desired thickness is achieved, the composite is cured and the mold is removed. This method typically produces a repeatedly high quality product, but it is difficult to achieve the irregular geometries that are sometimes associated with manholes and vaults, such as connections for pipes or valves, without disrupting the continuity of the fiber. Properties tend to be anisotropic in the longitudinal direction of the fiber.

In hand or manual lay-up, a mold of the desired structure is coated with a gel. The fiber reinforcement mat is cut to size and placed on the mold. The mat can either be applied pre-saturated with resin or dry, although pre-saturated is more desirable since it ensures more complete resin penetration into the fiber mat. Resin must then be squeegeed into the dry mat. The mat then needs to be hand-rolled or squeegeed to remove any air bubbles. This is repeated until the desired number of layers is achieved, and then the structure is cured to attain the finished product [14]. Hand lay-up enables the technician to align the reinforcement fibers manually to achieve the desired properties, even around complex geometries. However, because of the labor-intensive nature of the hand lay-up process, it tends to be a low-output method of production [1,15]. In addition, the quality of products manufactured by hand lay-up is highly dependent on the skill of the technician performing the work and, as such, may result in inconsistent performance of components. Because of its labor-intensive nature and variable quality output, hand lay-up is comparatively expensive and is being replaced by other manufacturing techniques [15].

Spray-up is an automated or manual production method in which a resin and chopped fiber are either separately or simultaneously sprayed onto the surface of a mold. A roller or squeegee is used to remove air and consolidate the composite. It is then cured and removed from the mold. Spray-up is highly conducive to producing irregular geometries. The process is less labor-

intensive than hand lay-up, and, thus, less expensive with higher production rates possible. Similar to hand layup, the quality of the part produced is still dependent on the skill of the spray gun operator. The spray-up process also eliminates the ability to specifically align the reinforcement, resulting in a product that has isotropic properties that are not suitable for high structural requirements [16].

Chop-hoop winding alternates discontinuous filament winding and chopped glass spray-up to provide the benefits of both fabrication techniques [12, 13]. This method provides manufactures with the flexibility to make irregular geometries and parts that have high strength, especially in the hoop loading direction. This process can be fully automated, and is gaining market share for cylindrical components such as manholes and vaults.

Manhole Covers

FRP composite manhole covers take advantage of the lightweight yet strong nature of composites and their low electrical and thermal conductivities. The light weight means FRP manhole covers are easier to handle and transport than the standard heavy and bulky cast iron covers, reducing the number of lifting injuries. The low conductivities protect workers and pedestrians from stray current or high heat in the utility tunnel. Composite manhole covers are highly corrosion resistant. Interestingly, fiberglass covers deter theft since there is no scrap value. Figure 3 shows before and after photos of cast iron frames and manhole covers replaced with FRP covers.



Figure 3. A lightweight and secure 36 inch Fiberglass Manhole Cover with frame installed after the cast iron manhole cover was stolen (left). The cast iron manhole cover in the photo on the right has been replaced with a fiberglass frame and cover that weighs 30 pounds and represents no scrap value [12].

Fiberglass manhole covers are typically manufactured using Resin Transfer Molding (RTM). RTM is a low pressure, closed molding process that offers a dimensionally accurate composite with a high quality surface finish [5]. Edge boil, when the center of the part reacts and cures at a faster rate than the outer edge, is a common problem during the manufacturing of FRP composite manhole covers—particularly those striving for the AASHTO M306 H20/H25 (40,000- and 50,000-pound proof loads, respectively) and European Standard EN 124-5 load standards [5,17, 18]. Excessive exothermic heat during curing causes the partially crosslinked resin on the outer perimeter to boil [5]. Decreasing the catalyst progressively during injection ensures a far more even cure and eliminates the edge boil [15]. The fiberglass covers and frames can be used on

both pre-cast concrete and fiberglass manholes; fiberglass manhole covers have been shown to exceed AASHTO H20 standards and meet EN 124 Class D400 requirements [12].

Structural Components (Beams, Gate Guides, etc.)

Structural components such as I-beams, wide flange beams, channels, tubes (square and round), plate, and bar are readily available off the shelf (Figure 4a). Custom or special shapes can also be manufactured. Structural components, such as rods, tubing (pipes), rails and other FRP composites with a consistent cross section and high volume demand, are manufactured using a pultrusion method. Because of the speed and consistency of this predominantly automated technique, it is the most common for manufacturing fiber-reinforced composites used in civil applications [15]. Reinforcement fibers are pulled through a resin bath and then pulled through a heated die, which cures the resin and consolidates the fibers.

Composite beams can be used for structural purposes in place of metal, for example as gate guides. They are lighter in weight than traditional steel components, which allows for ease of handling and installation (Figure 4b). Other uses for these pultruded parts will be discussed in the following sections.



Figure 4. (a, left) Components of a pultruded fiberglass structural beam [7] and (b, right) a pultruded composite beam showing the ease of handling due to the lighter weight compared to steel [7].

Gratings

Reclamation structures include a variety of uses for gratings including platforms and walkways, trash racks, and fish screens and brails. There are two methods used to manufacture composite gratings: pultrusion and molding. Figure 5 and Figure 6 show the fish brail structure at Keswick Dam and the pultruded and molded gratings utilized on the structure.



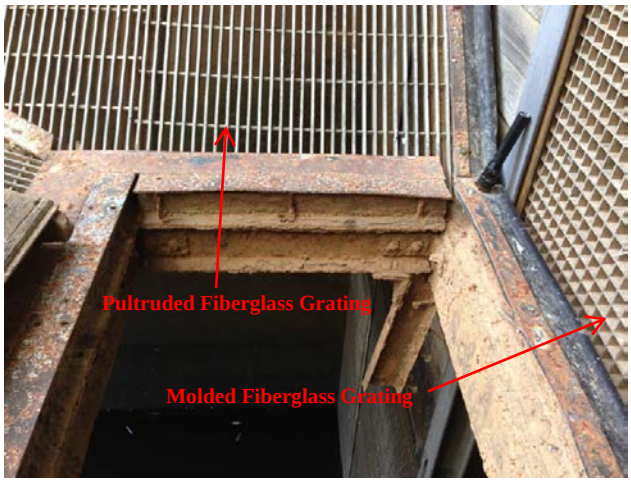


Figure 5. FRP gratings on Keswick Dam Fish Brail Structure.



Figure 6. Pultruded FRP gratings on Keswick Dam Fish Brail Structure.

Pultruded Gratings

Pultruded gratings are manufactured from FRP composite rods and rails that are then assembled into panels [19]. They have a higher glass content which makes them stiffer, and, thus, able to cover larger spans that molded gratings. This type of grating is used to construct trash racks, platforms, and walkways.

Molded Gratings

Manufacturing molded FRP composite gratings involves six basic process steps. First, fibers are woven around the mold blocks, typically stainless steel, to the top of the mold; then the resin is poured over the fibers, bathing them in resin [20]. Next, the mold is heated to cure the resin, after which hydraulic push rods lift the grating to release it from the mold. The surface of the grating is then polished, and the part is trimmed and cut to size [20]. Finally, a UV protective coating and/or non-slip coating is applied, if required.

Stairs, Handrails, and Ladders

Stairs, handrails, and ladders often are installed in locations where corrosion of the traditional metallic components is a common problem, such as full immersion in a tank or sump or exposure to a splash zone or spray environment. Corrosion of these structures can lead to significant safety issues, as shown in Figure 7. Using composite materials for stairs, handrails, and ladders can alleviate these corrosion failure issues and reduce the associated operation and maintenance costs.



Figure 7. Stairs (left) and ladder (center) in Owyhee Dam gallery; ladder (right) in Paonia Dam elevator shaft. All exhibit significant corrosion of the metal due to humidity, condensation, and water leaks.

Composite handrails are commercially available for stair rails, platform/walkway handrails, and guardrails [7]. These rails are fabricated from pultruded fiberglass components using a vinyl ester or a polyester resin system with molded thermoplastic connectors and stainless steel hardware. This makes these railing systems well-suited to corrosive environments and easy to install in the field since they require no welding. Handrails can be constructed of round components or square components as shown in Figure 8. Typical materials properties for square versus round rails can be found in Table III. The handrails meet Occupational Safety and Health Administration (OSHA) strength requirements with a 2:1 factor of safety with a 6-foot maximum post spacing, and they can be made to comply with Americans with Disabilities Act (ADA) standards upon request [7]. Many of these composite components include a UV inhibitor for additional resistance to ultraviolet degradation and corrosion. Custom handrails are also available for special requirements such as more complex shapes, two-color rails, increased loads, etc. A complete structure set-up showing FRP handrails, walkway/platform grating, and stair is shown in Figure 9a. An FRP composite ladder with safety cage is shown in Figure 9b. The final product can be shipped completely assembled depending on the size required and will make the installation easy and quick. The ladder and safety cage are an assembly of various pultruded FRP components and assembled with stainless steel hardware.





Figure 8. Round bar (left) in Fort Lauderdale, FL, on the 17th Street Bridge's fenders and square bar (right) walkways and emergency escape routes of the Chicago Transit Authority's rail lines. The handrail system is pultruded using a vinyl ester or a polyester resin system. The system includes an inhibitor for resistance to ultraviolet degradation [21].





Figure 9. (left) Complete FRP structure including handrails, walkway/platform grating, and stairs, and (right) FRP ladder with safety cage [12].

Table III. Typical materials properties for pultruded fiberglass composite railings [21].

Properties	Test Method	Units	Square Rail Values	Round Rail Values
Ultimate Flexural Stress (full Section)	N/A*	psi N/mm^2	36,000 248	60,000 414
Flexural Modulus (non-phenolic) (full section)	N/A*	psi x 10^6 N/mm^2	3.7 25,500	4.5 31,000
Flexural Modulus (phenolic) (full section)	N/A*	psi x 10^6 N/mm^2	6.0 41,400	6.0 41,400
Density	ASTM D792 [22]	lbs/in^3 g/cc	.065 – .075 1.80 – 2.08	.065 – .075 1.80 – 2.08
24hr Water Absorption (non-phenolic)	ASTM D570 [23]	% max by wt	0.6	0.6
24hr Water Absorption (phenolic)	ASTM D570 [23]	% max by wt	2.0	2.0
Coefficient of Thermal Expansion lengthwise	ASTM D696 [24]	10^{-4}in/in/°F 10^{-6}mm/mm/°C	7 1.2	7 1.2

* Test standard for these properties was not listed by manufacturer.

Small Gates and Stoplogs

Pre-impregnated fiber mats (prepregs) can be used to simplify and speed up the manufacturing process. These pre-impregnated materials are stored in a freezer to prevent the resin from curing prematurely. Specialized equipment places the fibers in the uncured resin, causing many prepreg materials to have isotropic properties [1]. There are two types of resins used depending on the desired properties for the final fiber-reinforced polymer composite. For prepregs with a thermoset resin, the fibers are positioned and the resin allowed to partially cure into the "B-stage" which is a pliable solid state. This state enables the material to be easily shaped. When curing prepregs with thermoset resins, heat is applied and the composite will permanently retain its shape. Materials pre-impregnated with thermoplastic resins are easier to handle, as they can be stored at room temperature. When the material is ready for use, it is heated and shaped. Vacuum bag molding is then used to partially pressurize and cure prepreg material [25].

Four glass fiber reinforced polymer wicket gates were installed at the U.S. Army Corps of Engineers (USACE) Peoria lock and dam. These gates were constructed using prepreg glass fiber mats and pressure supplied by a vacuum bag method. Figure 10 shows the original wooden construction gates and the replacement FRP composite gates. The wooden gates get damaged or degraded and the wood required to construct them is getting more difficult to acquire. The wooden gates also involve a significant amount of manual construction, making the cost fairly high. In relation, the FRP gates are less expensive to manufacture. The installed gates are shown in Figure 10.



Figure 10. USACE wicket gates at Peoria Lock and Dam. The gate on the left is the original wooden construction and the gate in the middle is the replacement FRP composite. The image on the right is the installed composite wicket gates being field-tested.

The slide gate in Figure 11a is reinforced to withstand the specified maximum operating head and neoprene j-seals can be included to provide low leakage rates [26].The stop logs shown in Figure 11b have been used for numerous applications over the last 18 years. Since they have no seams or cracks from mechanical construction they do not allow seepage like steel stop logs [26]. Water absorption is lower for the composites compared to wooden stop logs, decreasing the likelihood of poor sealing.



Figure 11. (left) Gray fiberglass reinforced polymer slide or sluice gate and FRP frame with UV inhibitors and (right) fiberglass stop logs used successfully over the past 18 years in numerous applications [26].

Composite Treatments

Many composite manufacturers offer customizable treatments, additives, fillers, or coatings for special applications or service requirements. Various fillers and inhibitors can be added to improve fire retardancy, mechanical properties, and UV degradation resistance. UV inhibitor is standard for many parts designed for outdoor applications, such as handrails, as is an industrial

grade polyurethane coating used as additional protection against fading [7]. Slip-resistant coatings can be requested for manhole covers and gratings on walkways. Many products can also be colored for inspection, safety, or aesthetic purposes, as shown in Figure 9.

Polymer Concrete

Polymer concrete, also referred to as resin concrete, is a variation of concrete where cement is replaced with synthetic resins and a hardening agent. Like traditional concrete, the filler is a mixture of sand and gravel. Polymers can also be combined with concrete, such as polymer-impregnated concrete and polymer-Portland cement concrete (polymer modified concrete) [27].

Polymer concrete may be used for new construction or repair of existing conventional cement-based concrete, in special circumstances, and polymer concrete structures. When used as a stand-alone component, such as vaults, manholes, and manhole covers, due to the difficulty of forming structures and quality control in the field, this material is best used as a precast component. Due to its low permeability and corrosion resistance, polymer concrete is useful in conditions where a structure needs to contain liquid, such as construction and rehabilitation of manholes [28]. It can also be used in highly corrosive soils, such as those where high sulfate content would attack conventional concrete. Precast vaults and manholes are shown in Figure 12. While polymer concrete has not been widely used due to the high costs and difficulty associated with traditional manufacturing techniques, recent progress has led to significant reductions in cost [28,29].



Figure 12. Precast polymer concrete vault (left) [30] and manhole (right) showing various openings for pipe or entry [31].

Polymer concrete manholes offer a corrosion resistant, leak-free, maintenance friendly and cost effective system. These manholes can be built to project specifications including sizes greater than 96 inch diameter [30]. The bond between resin and aggregate allows the manholes to withstand high compressive and bending loads with thinner walls and reduced weight compared to traditional concrete manholes [30]. Polymer concrete structures, like traditional concrete structures, may require steel or composite reinforcement per ASTM C478 [31].

Other uses of polymer concrete include bridge drainage systems (bridge edge beams, curbs, drainage inlets, gutters), linear drainage systems (channels, silt boxes), and storage tanks. The properties of polymer concrete compared to traditional concrete are shown in Table IV.

Table IV. Properties of polymer concrete with comparison to traditional 4000 psi concrete [32, 33].

	Polymer Concrete	Typical 4000 psi concrete
Compressive Strength R_c [MPa]	80 - 110	30
Bending Tensile Strength R_g [MPa]	22 - 35	2 - 4
Splitting Tensile Strength R_r [MPa]	8 - 12	1.5 - 2
Abrasion Resistance [cm]	0.1 - 0.3	0.6
Moisture Absorption [mm]	0	4 - 8
Apparent Density of resin concrete [kg/m^3] (avg)	2300	
Poisson's Ratio	0.16 - 0.30	
Relation of aggregate content to binder in resin concrete	6.5 - 11	
Linear Thermal Expansion Coefficient [1/°C]	17×10^{-6}	
Frost Resistance [cycle]	min 150	

Manufacturers

There is a wide variety of low-risk infrastructure applications for composite materials, some of which have been covered in the previous sections. As such, there are also many manufacturers of these products. Table V provides a partial list of some of these manufactures and the products they offer.

Table V. List of manufacturers of FRP and polymer concrete products*

Manufacturer	*Products*
Virtual Polymer Compounds, LLC	FRP Manholes and Covers, ladders, grating, hand rails
Armorcast Products Company	Polymer Concrete vaults and manholes, FRP vault and manholes
OPW Fibrelite	FRP manhole covers, trench covers
Composite Access Products	FRP manhole covers
Structural Fiberglass, Inc.	Ladders, handrails, grates
Fibergrate Composite Structures	FRP handrails, ladders, gratings
Strongwell	FRP handrails, ladders, grating, sheet piling, fabricated structural components
FRP Fittings Inc.	FRP Manways, covers, and grating
Plasti-Fab	Stoplogs, small gates, manholes, manhole covers, and ladders

* inclusion in this list does not indicate endorsement by Reclamation

Specifications and Design Standards

Specifications

Reclamation would likely write a performance specification for projects in which composite materials are an option, and such a specification would follow the general Reclamation guidelines for structures of that type. In particular, the specification should include information regarding:

- Materials- including type of composite (FRP, polymer concrete) and any restrictions on components; materials allowed for joints or anchors; special reinforcement, coatings, additives, coloring, or other treatments; standards that components should meet
- Manufacturing- is hand lay-up allowed or must process be automated; continuous versus chopped fibers; design standards that should be followed during manufacturing
- Dimension- size requirements including tolerances
- Performance Requirements- mechanical/load requirements; environmental performance criteria such as temperature tolerance, corrosion resistance, UV light exposure, fire retardancy, chemical resistance; any applicable standards
- Quality Assurance - including samples and/or test results that must be submitted to Reclamation for verification; define what would be grounds for rejection of a part
- Installation- including instructions on joining or sealing composite parts
- Storage and Handling- typically per manufacturer's recommendations

The following sections provide a partial list of standards that may be useful when specifying composite materials for low-risk infrastructure applications. The most current version of a standard should be used unless otherwise listed.

FRP Composite Standards

AASHTO M306	Standard Specification for Drainage, Sewer, Utility, and Related Castings
ASTM D638	Standard Test Method for Tensile Properties of Plastics
ASTM D695	Standard Test Method for Compressive Properties of Rigid Plastics
ASTM D790	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
ASTM C1028	Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method (Withdrawn 2014)
ASTM D2344/D2344M	Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates
ASTM D3039/D3039M	Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
ASTM D3171	Standard Test Methods for Constituent Content of Composite Materials
ASTM D3518/D3518M	Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate
ASTM D-3753-12E1	Standard Specification for Glass-Fiber-Reinforced Polyester Manholes and Wetwells

ASTM D7137/D7137M	Standard Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates
ASTM D7264/D7264M	Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials
ASTM D7522/D7522M	Standard Test Method for Pull-Off Strength for FRP Laminate Systems Bonded to Concrete Substrate

Polymer Concrete Composite Standards

ASTM C33	Standard Specification for Concrete Aggregates
ASTM C443	Standard Specification for Joints for Concrete Pipe and Manholes Using Rubber Gaskets
ASTM C478	Standard Specification for Precast Reinforced Concrete Manhole Sections
ASTM C497	Standard Test Method for Concrete Pipe, Manhole Sections, or Tile
ASTM C579	Standard Test Method for Compressive Strength of Chemical Resistant Mortars, Grouts, Monolithic Surfacing and Polymer Concretes
ASTM C857	Standard Practice for Minimum Structural Design Loading for Underground Precast Concrete Utility Structures
ASTM C923	Standard Specification for Resilient Connectors between Reinforced Concrete Manhole Structures, Pipes, and Laterals
ASTM D6783	Standard specification for polymer concrete pipe

Design Standards

AWWA C563	Fabricated Composite Slide Gates
ANSI/AWWA D107	Composite Elevated Tanks for Water Storage
ANSI/ASCE 3-91 and 9-91	Standard for the Structural Design of Composite Slabs and Standard Practice for Construction and Inspection of Composite Slabs
ANSI ASC A14	Ladder Standards
ASCE 23-97	Specifications for Structural Steel Beams with Web Openings
ASCE Manual No. 63	Structural Plastics Design Manual
ASCE/ACMA	Pre-Standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures (submitted to ANSI standards process)
ACMA	Code of Standard Practice – Industry Guidelines for Fabrication and Installation of Pultruded FRP Structures (submitted to ANSI standards process)
ASTM C478	Standard Specification for Precast Reinforced Concrete Manhole Sections
EN 124-1	Gully tops and manhole tops for vehicular and pedestrian areas. Definitions, classification, general principles of design, performance requirements and test methods

Comparison to Current Practice

Potential Benefits of Composites

- Due to their high strength-to-weight ratio, composite products typically weigh substantially less than precast concrete or steel products:
    - installation is accomplished with less manpower, time, and cost
    - specialized heavy equipment for transportation, installation, and in-service maneuvering is often not necessary
    - lower risk of worker injury due to lifting
- Properties are highly tailorable to specific applications based on design and matrix and reinforcement materials selections
- Many products can be manufactured in a single-piece design; this, combined with composites' low permeability to liquids, prevents leakage out of or into structures
- FRP composites can be easily field repaired
- Systems can be prefabricated in large sections and shipped to the site or fabricated in pieces in a factory and assembled on site with simple carpenter tools; drilling and cutting can be accomplished with standard diamond bits and saw blades
- Low electrical conductivity minimizes risk of shock to workers and public
- Low thermal conductivity minimizes risk of heat transfer and burn injuries
- Composites have a high corrosion resistance to chemical substances, including acids, bases, chlorides, and sulfates - they are more resistant to degradation than metals or concrete in burial and immersion service and do not require costly corrosion mitigation measures such as protective coatings or liners and cathodic protection
- Colorants provide permanent solution to project aesthetic requirements (no spot repair or re-coating required)
- Many composites, particularly polymer concretes, have high scratch, abrasion, and erosion resistance
- Good adhesion to essential constructional materials (steel, traditional concrete)
- Good ability to dampen vibrations due to resins contained in the material

Weaknesses / Cautions

- Limited experience by design professionals and contractors
- Light weight nature may require anchors to prevent movement
- UV inhibitors are required to prevent degradation
- FRP materials cannot be used for all loads and conditions
- Variety of off-the-shelf products is not as extensive as for traditional materials, which may mean a longer lead time for product availability
- Up-front costs for composite materials are often higher than for traditional building materials
- Making modifications to precast components in the field is more difficult for polymer concrete composites than for conventional concrete
- Some caution is required if utilizing accelerated test methods, as the test may not represent actual degradation mechanisms in the field over the full service life of a structure.

Cost

For low-risk infrastructure fiberglass products outperform precast concrete and steel in almost all aspects except one: product cost. Precast concrete and steel products are typically less expensive than fiberglass; however, the savings may be short lived. The initial purchase cost of the product may be higher, but once the additional costs associated with difficult installations, complex on-site repairs, and even replacing the entire product due to deterioration are factored in, fiberglass can be a more economical option compared to steel and concrete; ensuring a long-lasting and maintenance-free performance [13]. The long term cost benefits is shown effectively by the case study in Figure 13.



Figure 13. Galatia, Illinois coal preparation plant. The coal preparation environment resulted in significant deterioration of carbon steel within two years and stainless steel in less than six. Strongwell's SAFRAIL™ square tube industrial handrail combined with DURADEK® I-6000 grating and stair treads were installed in all areas of a new section. After sixteen years of service, Strongwell revisited the plant in 2012. There had not been a single corrosion related problem, while the metal structures and components around the fiberglass railing and platforms were failing [7].

Polymer concrete can be beneficial as a low-risk infrastructure component versus ordinary Portland cement (OPC) concrete applications. Initial product cost will be higher for polymer concrete versus OPC. Polymer concrete offers several advantages to OPC, including higher minimum compressive strength, higher minimum tensile strength, higher minimum bending strength, lower maximum moisture absorption, better freeze-thaw durability, impermeable, permanent colors if desired, and abrasion resistance [32,33]. These attributes will require less maintenance and repair therefore cost less in the life of the material.

Recommendations for Implementation

Many low-risk infrastructure components could be installed with few changes to Reclamation performance specifications. Some examples of components that are already being produced from multiple manufacturers include: gratings, common structural shapes, guardrails, handrails, ladders, stairs, stair treads, manhole covers, trench covers, work platforms and many custom applications. Testing procedures already exist for these components, and quality assurance testing could be adopted by Reclamation.

Other structures, such as trash racks, rack rake teeth, and remote canal gates require further investigation prior to specification on Reclamation projects. These structures are often custom-produced components, and the monetary investment is larger than for some of the off-the-shelf products listed previously. Current installations of composites at Reclamation and the Corps of Engineers should be scrutinized for lessons-learned. Quality assurance procedures would need to be developed for verification of delivered products.

Life cycle cost analysis should be performed versus traditional materials for each type of structure before wide-spread implementation.

Opportunities for Additional Research

This report has presented an overview of the use of composite materials in many types of low-risk infrastructure applications. However, it is difficult to make broad generalizations about FRP and polymer concrete composites because of the variety of component materials, designs, and manufacturing process used. It would be useful to compile specific information for each type of structure mentioned, including tracking current installations or conducting pilot studies. While many of these products are gaining market share, there are still questions regarding the long-term performance and life-cycle costs for composite structures in Reclamation service conditions and how those compare to traditional materials. In addition, it would be pertinent to gather information that would anticipate inspection and maintenance requirements for composite structures.

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Appendix D: Testing Composite Materials

RECLAMATION

Managing Water in the West

Technical Memorandum No. MERL-2015-033

Testing Composite Materials



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

September 2015

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BUREAU OF RECLAMATION
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Executive Summary

Reclamation continually strives to use better, longer lasting, and sustainable materials for its infrastructure, and modern composite materials, such as fiber reinforced polymer (FRP) composites or polymer concrete, offer a viable alternative to traditional construction materials in many applications. However, the selection of a new material requires an understanding of performance under the anticipated service conditions. Although composites have been on the market for several decades, new production methods, component designs, and intended applications are frequently introduced with little historical field data. Laboratory testing can provide a way to determine estimated lifetime and performance of a new material in a simulated service environment.

The purpose of this paper is to summarize available testing standards and their suitability for providing feedback on the quality of composite materials that are of interest for Reclamation projects. Reclamation should evaluate each new application of composite materials and determine on a case-by-case basis what tests or inspections would be required in a specification for quality assurance and acceptance of a product. Reclamation should also ensure that manufacturers have a good quality control program in place for any new composite products that come on the market. This report is intended to aid in selection of appropriate standardized and commonly used test methods for composite materials.

The tests presented have been selected primarily based on references from standard specifications as well as their common usage by composites manufacturers. The standards referenced are from organizations including American Society for Testing and Materials (ASTM), American National Standards Institute (ANSI), International Organization for Standardization (ISO), European Standards (EN) and America Water Works Association (AWWA). Several manufacturers were contacted with regard to typical and reported testing regularly employed on their products. The manufacturer list was compiled from accompanying Reclamation reports on composites for coatings, low-risk infrastructure, and pipelines, and was limited to those manufacturers located in the United States. Testing methods are presented in the categories of weathering, moisture absorption, ultraviolet light exposure, freeze/thaw cycling, chemical resistance, physical durability, and engineering properties. The most commonly used tests are tabulated and include the property tested, the designation, and the relevant type of infrastructure.

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Introduction

Reclamation continually strives to use better, longer lasting, and sustainable materials for its infrastructure. Current metal and concrete materials can suffer degradation in many Reclamation exposure conditions. Using modern composite materials, such as fiber reinforced polymer (FRP) composites, which typically provide a longer service life in these conditions, would lower maintenance costs and improve performance. Reclamation spends significant money repairing, recoating, and continually maintaining many of its structures. Finding new material alternatives will allow for a cost-effective, long-term replacement of current damaged or deteriorated structures.

The selection of a new material requires an understanding of performance under the anticipated service conditions. Laboratory testing provides a procedure for determining estimated lifetime and performance of a new material in an environment. While composites have been in existence for several decades, new production methods, component designs, and intended applications are being introduced frequently. Because of this relatively new entrance to the market, there is not a wealth of historical knowledge that can be used to predict service life, making laboratory testing all the more important.

Reclamation structures are exposed to a variety of environmental conditions that can affect service life. Freeze/thaw weather cycles, humidity, immersion, and ultraviolet (UV) light degradation are among the conditions that can reduce service life of structures. Degradation in alkaline and acidic conditions is also an important condition that affects metals and concrete. Abrasion, erosion, and impact damage from debris occurs on a number of structures under Reclamation's purview. All of these degradation mechanisms typically occur over long time scales that are not practical for quality control testing; hence the need for accelerated testing protocols.

The purpose of this paper is to summarize available testing standards and their suitability for providing feedback on the quality of composite materials that are of interest for Reclamation projects. It is intended to aid selection of appropriate tests and inspections to be included in Reclamation specifications for quality assurance and acceptance of composite products. The tests have been largely collected from the American Society for Testing and Materials (ASTM) Committee D30 on Composite Materials and Committee D20 on Plastics, but have also included other standard specifications including those from American National Standards Institute (ANSI), International Organization for Standardization (ISO), European Standards, (EN) and America Water Works Association (AWWA). The tests summarized are chosen based on references from the standard specifications mentioned above and their cited use by various composite manufacturers.

For the purposes of this report, composite materials are divided into three major categories of interest to Reclamation: coatings, low-risk infrastructure (such as manholes, vaults, gratings, gate guides, trashracks, handrails, etc.), and pipelines. Further detail on each of these topic areas is included in the accompanying reports.

Summary of Tests and Procedures

One of the best resources for testing procedures is the ASTM committee D30 on composite materials. They have issued a *Standard Guide for Testing Polymer Matrix Composite Materials* (ASTM D4762) which summarizes commonly used test methods. Many standards and references are also mentioned in the Composite Materials Handbook (CMH-17 or MIL-HDBK-17). Several of the tests from ASTM committee D20 on plastics are also relevant for composite materials [1].

All of the tests relating to the three composite categories- coatings, low-risk infrastructure, and pipelines- are given in the Composite Material Tests Table in Appendix A. The tests are organized into the following categories: construction, corrosion/chemical attack, creep/fatigue, design, electrical, fire, freeze/thaw, hygrothermic, impact/erosion/abrasion/cavitation, mechanical properties/performance, moisture absorption, quality control, rehabilitation, safety, specification, temperature cycles, ultraviolet (UV) light, and weathering. The headings include the standard designation, the material tested, and the exposure condition. The rest of the table is a cross-reference to a standard specification or manufacturer that references the test. The specifications and manufacturers are organized based on the composite category in which they fall, including a general category. The specifications and manufacturers are numbered for clarity, and, if the test is referenced by the specification or manufacturer, the same number appears in the corresponding cell. This provides a way to glance over the table for most commonly referenced or used tests. The commonly referenced or used tests from the Composites Material Tests Table (Appendix A) are summarized below in common Reclamation test categories: weathering, moisture absorption, UV light exposure, freeze/thaw cycling, chemical resistance, physical durability, and engineering properties. A description of the test along with the reason for its use is given, and, in some cases, alternative tests are provided. Finally, in the conclusion, a list of these tests is given as a quick reference guide in Table I: Summary of Composite Tests.

Weathering

Weathering tests are designed to simulate natural weathering processes. Here individual effects from sunlight, moisture, temperature, and atmospheric pollutants are combined. ASTM D1014, *Standard Practice for Conducting Exterior Exposure Tests of Paints and Coatings on Metal Substrates*, and ASTM G7, *Practice for Atmospheric Environmental Exposure Testing of Nonmetallic Materials*, are examples of simple non-accelerated weather tests. The sample is placed in a location as near in exposure conditions as the proposed placement of the final product and observed over a period of time, usually for one year. Climate data, such as the radiant energy, temperature, rainfall amounts, humidity, and concentration of pollutants, are recorded. Deterioration indicators, such as cracking, blistering, chalking, mass loss, color change, and strength loss, are used to evaluate the samples in accordance with other standardized tests. Both tests warn that a single year's worth of data may not be representative of long-term conditions, as well as encourage testing in several locations with different climates for a more accurate service life prediction. These tests are applicable to sample sizes that can be oriented to face in a

particular direction, e.g. south facing, whereas components in the field may not have the same exposure on all sides (see Figure 1).



Figure 1: Sample exposure racks for natural weathering tests [2]

Instead of waiting several years or decades to thoroughly test materials, weathering tests are often accelerated by combining the exposure of the different weathering components such as moisture and temperature cycles or moisture and UV light. ASTM D5894, *Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal, (Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet),* is an example of one of these tests. This test is performed by exposing the sample to one week of exposure to UV light and condensation cycles followed by a week of exposure to salt fog and drying cycles.

Several other types of weathering and accelerated weathering tests are referenced by ASTM D1654, *Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments,* which is a test meant to evaluate a sample exposed to a choice of a variety of exposure conditions (Figure 2). These conditions include salt spray (ASTM B117), modified salt spray (ASTM G85), water fog (ASTM D1735), humidity (ASTM D2247), water immersion (ASTM D870), UV-condensation (ASTM D4587), solar concentration (ASTM D4141), carbon-arc exposure (ASTM D822), Xenon-arc (ASTM D6695), and sulfur dioxide (SO_2) (ASTM G87) and depend on the expected exposure condition or conditions of the installed coating. The modified salt spray test includes acetic acid-salt spray, acidified salt spray, seawater acidified testing, SO_2 salt spray and dilute electrolyte fog testing. While these tests have been designed for testing coatings and paints, they can also be used to evaluate exposure of composite panels.



Figure 2: Reclamation Cyclic Corrosion Chamber (salt spray)

The relative performance of materials under these testing conditions should be compared to results from control samples or other standard exposure conditions. It should be noted that no accelerated or laboratory weathering test can be considered to completely reproduce conditions that occur in an actual exposure condition. In cases where such a comparison is to be made, a statistical degree of rank correlation should be developed. In addition, conclusions about the relationship between accelerated testing and exterior exposures should be carefully considered and used with caution when trying to predict service life deterioration [3].

Moisture Absorption

Most of Reclamation's infrastructure is located within or in close proximity to water. As such, durability under humid or immersion conditions is important for structural materials. Moisture absorption is defined as the capacity of a material to absorb or take on moisture from its environment; it is a function of exposure time, temperature, and humidity, and applies to most materials in atmospheric or immersion service. The effects of moisture absorption include hydrolysis, plasticization, saponification and other mechanisms that cause both reversible and irreversible changes to a polymer's structure [4]. These structural changes, in turn, affect the mechanical and chemical properties, and hence performance, of many materials, especially organic polymers that compose the matrix phase of composite materials [5]. Moisture absorption testing should be performed on any composite material exposed to humidity, rain, or immersion.

There are two tests identified as moisture absorption tests. ASTM D570, *Standard Test Method for Water Absorption of Plastics*, associated with plastics, is used by many composite industry manufacturers including producers of pipelines, low-risk infrastructure, and coatings. The tests are simple and can be performed on samples removed from the finished product. The test specifies a choice of immersion durations and temperatures, though many companies report results using a 24-hour test at near room temperature [6] [7].

The second test, ASTM D5229, *Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials*, associated with FRPs, describes several procedures in different moisture and temperature conditions, as well as different

liquids (other than water) and gases. The conditions of the test should be determined based on the expected service conditions.

Ultraviolet Light Exposure

UV light exposure is one of the most commonly observed deterioration processes that affect the resin (polymer) matrix component of composite materials. Thus, it affects a wide range of potential applications for composites at Reclamation, including exposed pipeline, manhole covers, grates, handrails, ladders, and surface coatings. While the exact physical results differ between types of epoxy resins, the main degradation mechanism is that the energy from photons in the UV wavelengths of the spectrum is absorbed by the polymeric chain. This weakens and eventually destroys molecular bonds, leading to weak residue and erosion of the organic material. Observed physical indicators of UV degradation include chalking, glazing, hazing, and stress cracking [8].

Besides using concentrated sunlight as an accelerated UV method (not used by any manufacturers), there are three types of artificial UV light sources: carbon-arc, xenon-arc, and fluorescent lamps. Carbon-arc testing was introduced early in the 20th century and has been the historical standard "UV" test [9]. However, carbon-arc testing has the least conforming wavelength irradiance pattern of all sources. Xenon lamps showed up in the 1950's and, with the proper filters, have better correlation to sunlight, and adjustments can be made to compensate for intensity decay from lamp aging. Fluorescent UV lamps simulate the damage caused by sunlight by reproducing the critical UV portion of the light spectrum. Today, most manufacturers use either the Xenon lamps or the Fluorescent UV testing, though the Fluorescent UV test is the most widely used [10].

The test methods for Xenon weathering of plastics and coatings are ASTM D2565, *Standard Practice for Xenon-Arc Exposure of Plastics Intended for Outdoor Applications*, and D6695, *Standard Practice for Xenon-Arc Exposures of Paint and Related Coatings*, and the test methods for Fluorescent UV weathering of plastics and coatings are ASTM D4329, *Standard Practice for Fluorescent Ultraviolet (UV) Lamp Apparatus Exposure of Plastics*, and D4587, *Standard Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings* (Figure 3). All tests include temperature, UV, and moisture cycling options.



Figure 3: Reclamation Fluorescent UV Test Chamber

Freeze/Thaw Cycling

Freeze/thaw deterioration is a unique attacking mechanism of water caused by volume expansion when changing from liquid to solid or freezing. If composite matrices absorb water, or if cracking or delamination of the matrix from the reinforcement allows water to infiltrate the material, cycling between freezing and thawing temperatures can lead to severe damage to the mechanical integrity of a structure. Note that none of the manufacturers' data reviewed for this article, nor any standards or specifications, tested composite materials for freeze/thaw. However, since the exposure locations for composites within Reclamation are often immersed in, contain, or otherwise are exposed to water in freezing conditions, freeze/thaw testing would be highly recommended.

While there are no freeze and thawing tests that are specific to FRPs, plastics, or coatings, the method for concrete can be applied: *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (ASTM C666)*. The test features two procedures, with the most applicable method for immersion service being freezing and thawing in water (Procedure A), because it is the most aggressive and represents elements in constant contact with moisture. Procedure B, freezing in air and thawing in water, is more applicable for burial or atmospheric service, and either of these can be used as models for developing a freeze-thaw test specific to a service environment.

Chemical Resistance

Chemical agents present in soil or water, either natural or contaminant, can work in conjunction with available water sources to degrade a composite matrix. Typical chemical accelerators found under Reclamation service conditions include fertilizer runoff, chlorides, sulfates, and acidic or basic pH.

ASTM C581, *Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service*, is the standard for testing composites used in water control structures. This test does not outline specific reagents for testing the composite; instead it recommends the chosen reagent to represent the service exposure

condition. ASTM D543, *Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents*, offers a list of potential reagents that could be used for testing. The potential reagents include an acid solution (hydrochloric acid), a base solution (sodium hydroxide), chloride solution (sodium chloride), sulfate solution (sulfuric acid), hard water (sodium carbonate), and a baseline of distilled water.

For pipes, another ASTM applies: ASTM D3681, *Standard Test Method for Chemical Resistance of "Fiberglass" (Glass–Fiber–Reinforced Thermosetting-Resin) Pipe in a Deflected Condition*. Unlike ASTM C581, where the performance of the composite is measured by the hardness and other physical and mechanical properties after exposure, ASTM D3631 tests the deflection of the pipe while exposed to the reagent.

Physical Durability

Many of Reclamation's structures that would be candidates for construction with composite materials are located in proximity to moving water, including trash racks, fish screens, and gates. This water often carries debris, particles, and friction forces that can impact, erode, and abrade the surface. Cavitation-erosion is also a problem on some Reclamation structures, such as the turbine blades in hydropower plants. The standards listed below provide an estimate of a material's resistance to impact and cavitation damage.

The most common impact test is ASTM D256, *Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics*. ASTM D2794, *Standard Test Method for Resistance of Organic Coatings to the Effects of Rapid Deformation (Impact)*, and ASTM G14, *Standard Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test)*, are also used on coatings and coated pipeline applications. ASTM D256 involves the use of a weighted pendulum that is allowed to impact the specimen (Figure 4). If the hammer does not completely break through the specimen, a larger weight is added until failure occurs. Impact failure is recorded in terms of energy required to fail the specimen. Both ASTM D2794 and G14 use the same principle for applying energy to the specimen: gravity accelerated weights directed to the specimen within a guide. For D2794, the energy from the weight is transferred to a steel punch resting on the specimen, and in G14, the weight (or ram) is allowed to directly impact the specimen. The shapes of the indenters also vary based on the test: for D2794 (coatings on panels) the indenter shape is hemispherical, while in G14, the indenter shape is a perpendicularly oriented cylinder.



Figure 4: Izod Impact Strength Test Machine [11]



Figure 5: ASTM D4060 Taber Abrasion Tester

Several standards have been employed for abrasion erosion including ASTM C501, *Standard Test Method for Relative Resistance to Wear of Unglazed Ceramic Tile by the Taber Abraser*, D4060, *Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser*, G65, *Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus*, and G77, *Standard Test Method for Ranking Resistance of Materials to Sliding Wear Using Block-on-Ring Wear Test*. The most widely used standard is ASTM D4060. All of these tests are similar in function and feature a method of constantly contacting the specimen with an abrasive surface or medium.

ASTM D4060 uses a commercially available apparatus, called a Taber abraser, to subject the specimen to wear caused by abrasive wheels that are in contact with the specimen. The wheels are oriented to provide a perpendicular abrasion direction in order to test the resistance in materials that feature unidirectional or multidirectional fibers (Figure 5).

The only cited test by a manufacturer for cavitation was ASTM G134, *Standard Test Method for Erosion of Solid Materials by Cavitating Liquid Jet*, though ASTM G32, *Standard Test Method for Cavitation Erosion Using Vibratory Apparatus*, may also be applicable. ASTM G134 is a test that uses a jet to create cavitation bubbles on the material to cause erosion. ASTM G32 is an alternative method where the specimen is vibrated with enough frequency and amplitude to cause cavitation. The difference between the two methods is not only the way that the cavitation is caused but also which variables can be controlled. In ASTM G134, the jet velocity and downstream pressure are controlled, while in ASTM G32, the amplitude of the cavitation frequency is a variable. While ASTM G32 is a small-scale and simple test, it is not recommended for elastomeric coatings (refer to the Significance and Use and Scope sections of the standard).

Engineering Properties

Engineering properties include those parameters, particularly mechanical properties, which are used in the design of the material for its particular application. These properties are often used as quality control, with the rational being that if the material cannot meet the intended loading conditions, it will ultimately fail. The four main engineering properties include tension,

compression, shear, and flexure. Other properties that may contribute to the four main properties include stiffness, hardness, hydraulic pressure, adhesion or pull-off strength (in the case of a coating), and thermal expansion.

Tensile Strength

The most widely cited tensile tests by specifications and manufacturers are ASTM D3039, *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, and D638, *Standard Test Method for Tensile Properties of Plastics*. ASTM D3039 is typically used for high modulus specimens with continuous fibers, and ASTM D638 is more often used for low modulus specimens and discrete fibers [12]. ASTM D2105, *Standard Test Method for Longitudinal Tensile Properties of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Tube*, is another popular tension test for sections of pipe. The size of the pipe is generally limited to six inches, though it is applicable to larger diameters if the required testing fixtures are available.

Compressive Strength

Most of the specifications and manufacturers that were reviewed for this report give references and report the compressive strength from ASTM D695, *Standard Test Method for Compressive Properties of Rigid Plastics.* However, some claims are made that the combined loading compression (CLC) test (ASTM D6641, *Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture*) is the most-used compression test for composite materials [13]. The CLC test is specifically intended for polymer matrix composite materials; D695 is applicable to rigid plastics. The CLC methods is restricted to untabbed or tabbed flat panels, while the D695 method is more versatile with a procedure for sheets, plates, rods, tubes or other similar forms (see Figures 6 and 7).



Figure 6: ASTM D695 Test Fixture [14]

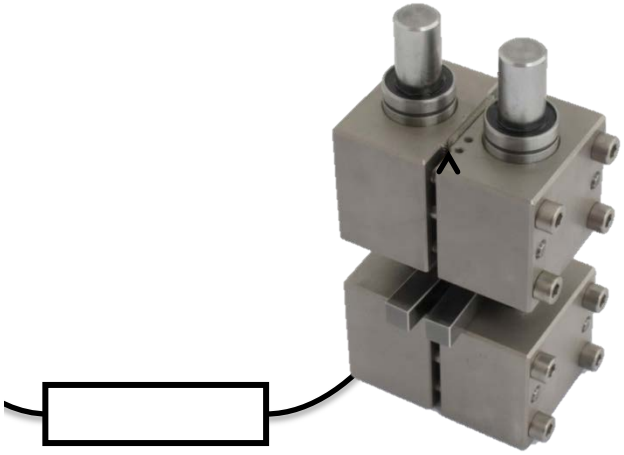


Figure 7: ASTM D6641 Test Fixture [15]

Flexural Strength

Flexural strength standards, similarly to compression strength standards, have two widely used procedures: the most cited test is applicable to plastics (ASTM D790, *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*), while some manufactures refer to a test specifically for polymer matrix composite materials (ASTM D7264, *Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials*). The D790 procedure is applicable to rectangle beams directly molded or cut from the parent shape. The D7264 test is appropriate for flat composite panels (Figure 8).

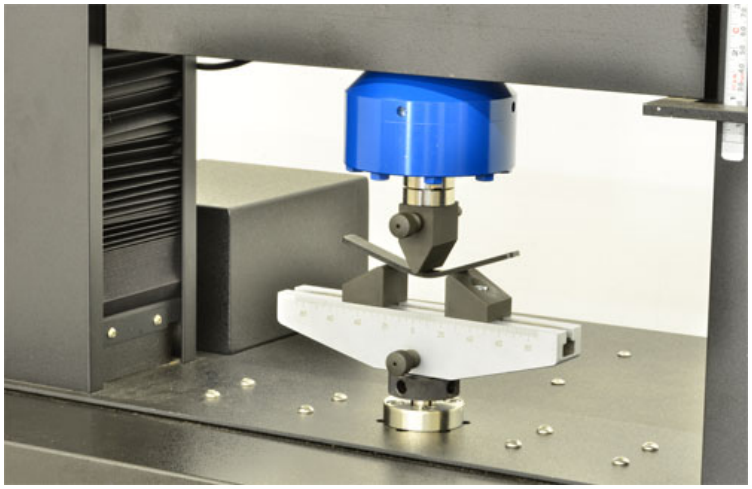


Figure 8: ASTM D790 and D7264 Test (D7264 also allows four-point loading) [16]

Shear

Shear is not commonly tested by manufacturers of composite products, and only two tests were mentioned: ASTM D3518, *Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate*, and ASTM D5379, *Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method*. The D3518 test is only the in-plane shear strength test for continuous fiber composites with laminates oriented at ± 45° to the loading direction. In this case, loading the specimen in tension with the fibers oriented at ± 45° induces the in-plane shear stress in the specimen, and the failure strength is used to calculate the shear stress (Figure 9). The D5379 test can be used to evaluate both in-plane or interlaminar shear properties by preparing a rectangular coupon with a machined notch on either side of the specimen. This notch is used to concentrate the shear forces during testing where the load is applied in opposite directions to either side of the coupon (Figure 10).

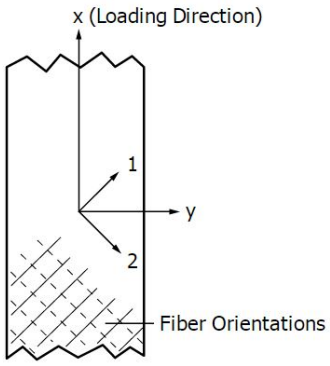


Figure 9: ASTM D3518 Loading

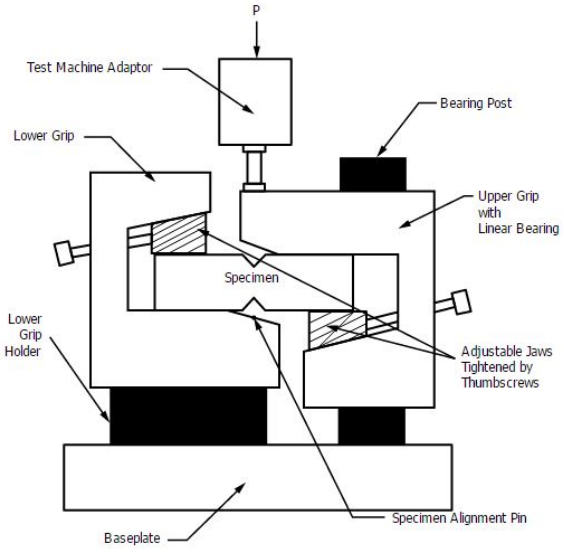


Figure 10: ASTM D5379 Loading Setup

Another shear-type test that is sometimes performed on low-risk infrastructure components is ASTM D2344, *Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates*. Here the sample span to thickness ratio is limited to 4:1 and can give reasonable estimates of the actual shear strength using a three-point bending setup [17]. The standard warns that the shear strength should not be related to any one material property and that its use should be limited for quality control or process specification purposes.

Stiffness

Stiffness is primarily a property that affects the serviceability of pipe. Pipe stiffness is a measure of the deflection of the pipe under a load and, more specifically, a soil backfill load. ASTM D2412, *Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading*, gives a procedure for determining the pipe stiffness and is theoretically applicable to any size pipe depending on the testing equipment capabilities (Figure 11).

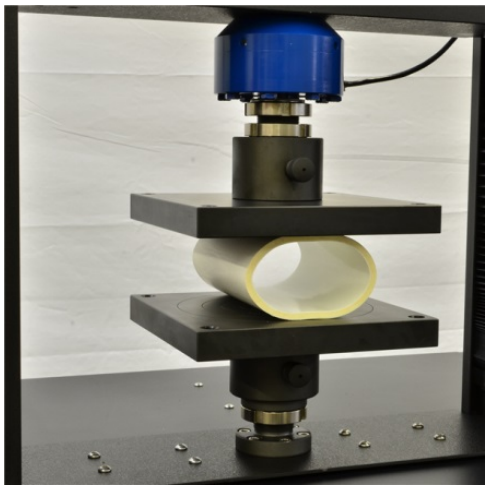


Figure 11: ASTM D2412 Test [18]

Hardness

Hardness in a composite material can be used to estimate how well the resin has cured or, indirectly, as an estimate of its durability. ASTM D2240, *Standard Test Method for Rubber Property—Durometer Hardness*, is the well-known hardness test, though in composites it is usually only applied to composite coatings, not bulk composite specimens (Figure 12). ASTM D2583, *Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor*, can be used to test composite coatings, as well as bulk samples, for example for low-risk infrastructure applications such as materials for gratings or manhole covers (Figure 13). The Durometer hardness is more applicable to low modulus materials and the Barcol method for more rigid materials. In either case, no relationship should be inferred between the hardness and the material's strength.

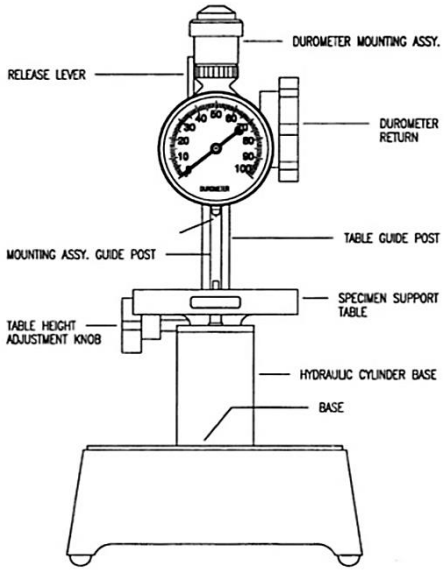


Figure 12: Diagram of Durometer Stand

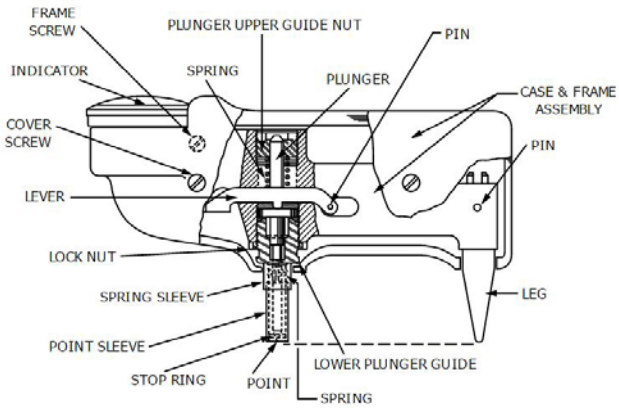


Figure 13: Diagram of Barcol Impressor

Pressure Testing

ASTM D1599, *Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings*, addresses the internal pressure limits in piping (Figure 14). References are made to this standard in some infrastructure ASTM specifications such as D3299 for water tanks and D4024 for flanges. It should be noted that, while flanges are mostly related to piping, other types of liquid containment components may also require flanges for connections to liquid conveyances. D1599 is a popular test because it simulates service conditions by controlling variables such as temperature, loading, and other stresses, and it can be used to verify compliance to minimum pressures (Figure 15).



Figure 14: ASTM D1599 Test Chamber [19]

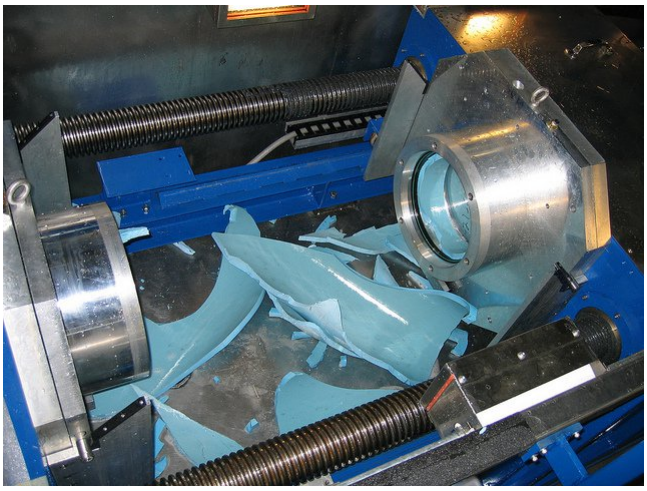


Figure 15: ASTM D1599 Failure [19]

Adhesion

Adhesion and pull-off strengths of composites refer mainly to coatings and/or strengthening techniques, though strengthening of structural components is not covered in this test summary. There are two test methods commonly identified: ASTM D4541, *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers* and ASTM C633, *Standard Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings*. D4541 is a popular and convenient test that uses an adhesion testing machine to test either the in-situ or laboratory prepared coatings on metal substrates (for concrete substrates see ASTM D7234). The setup consists of affixing a dolly or stud to the applied coating and then applying a concentric load to the dolly to pull off the dolly (Figure 16). C633 is not as commonly cited as D4541, mainly because it requires more preparation time and it can only be performed in the laboratory (Figure 17).



Figure 16: ASTM D4541 Portable Adhesion Tester Type V (Method E)

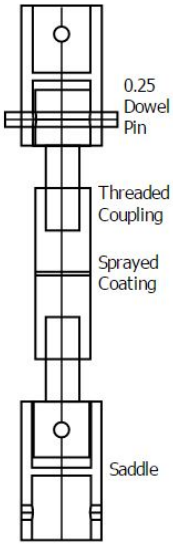


Figure 17: ASTM C633 Test Jig and Setup

Thermal Expansion

Thermal expansion is a property that may need to be verified or determined for certain configurations of composite components, especially those in direct contact with other materials such as steel. ASTM D696, *Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between −30°C and 30°C with a Vitreous Silica Dilatometer*, is the method most used and reported by coatings, low-risk infrastructure, and piping manufacturers. The temperature range covered in the standard is the basic serviceability range for most installations; however, if temperatures are expected to exceed this range, ASTM E228 can be used.

Fatigue and Creep

Fatigue is the accumulation of damage in a material during repeated loading cycles; creep is the tendency of a material to deform due to sustained loads. For structural components, including those made from composite materials, these are critical failure modes. In both cases, absorbed moisture and harsh environments have the potential to reduce the material's resistance to deformation and microcracking. Fatigue loading is not always mechanical and can be caused by thermal or chemical exposures as well [4].

Fatigue testing can be performed for all applications of composite materials and fatigue failure mechanisms are especially critical in pipeline applications [20]. ASTM D2992, *Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings*, is used in research and by at least one manufacturer for fatigue testing [21]. This standard is used to provide the design basis for the composite pipe using

two procedures, A and B. Procedure A is the cyclic or fatigue-based test and Procedure B is a long term static test.

Creep failure is not as commonly reported or tested by the manufacturers contacted for this report. ASTM D2990, *Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics*, can be applied to composites materials and used to provide creep behavior in tension, compression, and bending depending on the application. Another test method related to pipeline is provided by ISO 7984, *Plastics piping systems — Glass-reinforced thermosetting plastics (GRP) pipes — Determination of the creep factor under dry conditions*. However, moisture can also affect the resistance of the material to sustained long-term loadings, and the pipe should be tested in this condition as well [22]. The test that can be used to test creep under wet conditions is the European standard EN 1227:1997, *Plastics piping systems - Glass-reinforced thermosetting plastics (GRP) pipes - Determination of the long-term ultimate relative ring deflection under wet conditions*.

As mentioned above, there are many procedures and configurations for loading and testing composite components for various mechanical properties. The summary given covers the basic properties, as well as some more commonly reported properties. If the loading or testing condition does not fall in these categories, refer to ASTM D4762, ASTM Committee D30, D20, or the Composite Materials Handbook for additional guidance.

Reclamation Testing Capabilities

Reclamation has environmental testing equipment capable of examining materials under controlled temperature, UV light, humidity, salinity, and immersion exposure. Reclamation has both large scale (refrigerator or room-sized) and small scale (bench-top) environmental testing chambers (Figure 18). Currently, this equipment is used for coatings performance evaluations, concrete performance, accelerated corrosion performance, and creep testing etc.



Figure 18: Reclamation Environmental Chambers

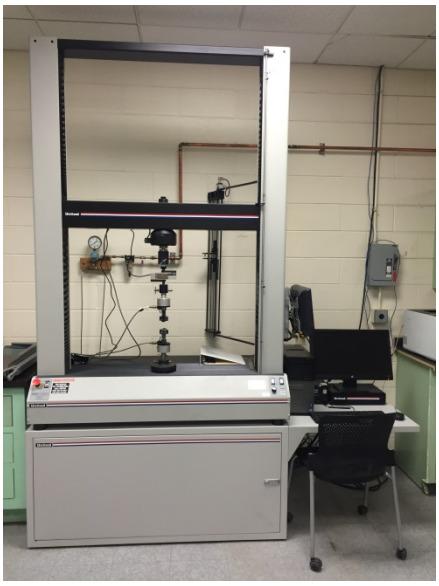


Figure 19: Reclamation Universal Testing Machine

Reclamation's corrosion laboratory houses equipment for performing accelerated corrosion and degradation testing in acidic or basic environments or those with high concentrations of chlorides or sulfates. The coatings laboratory offers several unique capabilities for testing the health and durability of organic coatings, which could be applied to composite coatings or matrix resins, and, in some cases, bulk composite samples. These include electrochemical impedance spectroscopy (EIS), abrasion testing, and accelerated erosion testing. In addition, Reclamation is in the process of building equipment and establishing protocols for cavitation testing (ASTM G134), specifically designed for coatings and has submitted a Reclamation standard for accelerated erosion testing to ASTM.

Reclamation's mechanical testing equipment includes multiple forms of tensile, compression, flexural, shear, torsion (wire only), and dynamic apparatus and fixtures (Figure 19).

The U.S. Army Corps of Engineers (USACE) has a mutual interest in composite materials and can perform many of the tests indicated in the Composite Materials Test Procedures Table (Appendix A). They have universal testing machines with additional fixtures to perform short beam strength tests and compression after impact testing. USACE also has testing capabilities for tension, compression, pull-off testing, flexural testing, etc.

Conclusions and Recommendations

Making service life predictions is difficult without testing a material in real exposure conditions. While composites have been in existence for several decades, new production methods, component designs, and intended applications are being introduced frequently. Because of this relatively new entrance to the market, there is not a wealth of historical knowledge that can be used to predict

service life, making laboratory testing all the more important. Although many laboratory tests do not have direct correlation to real world exposure conditions, and the results should be carefully studied and interpreted, the proper application of testing protocols contributes to knowledge of the material behavior and can be used to determine if the material will be suited to intended service application.

Reclamation should evaluate each new application of composite materials and determine on a case-by-case basis what tests or inspections would be required in a specification for quality assurance and acceptance of a product. Reclamation should also ensure that manufacturers have a good quality control program in place for any new composite products that come on the market.

The tests presented in this report have been selected primarily based on references from standard specifications as well as their common usage by composites manufacturers. The specifications referenced include ASTM, ISO, EN, ANSI, and AWWA. Several manufacturers were contacted with regard to typical and reported testing regularly employed on their products. The manufacturer list was compiled from accompanying Reclamation reports on composites for coatings, low-risk infrastructure, and pipelines, and was limited to those manufacturers located in the United States. Table 1 below outlines the most commonly used tests summarized above. In Appendix A, a comprehensive list of testing procedures can be found. This list is organized based on the testing category and relevant type of infrastructure.

Table I. Summary of Composite Tests

Exposure Category	Standard Designation	Composite Category	Test Condition
Weathering	ASTM D5894	All	Salt fog/UV
Weathering	ASTM D1654	All	Salt spray, fog, humidity, immersion, UV-condensation, solar, carbon- and Xenon-arc, and sulfur dioxide
Moisture Absorption	ASTM D570	All	Immersion
UV Exposure	ASTM D2565	Low-risk and pipe	Xenon-arc
UV Exposure	ASTM D6695	Coatings	Xenon-arc
UV Exposure	ASTM D4329	Low-risk and pipe	Fluorescent UV
UV Exposure	ASTM D4587	Coatings	Fluorescent UV
Freeze/Thaw	ASTM C666	All	Immersed freezing and thawing
Chemical Resistance	ASTM C581	All	Relevant reagent
Chemical Resistance	ASTM D3681	Pipe	Relevant reagent
Physical Resistance	ASTM D256	All	Impact (Izod)
Physical Resistance	ASTM D4060	All	Abrasion (Taber)
Physical Resistance	ASTM G134	All	Cavitation
Engineering Properties	ASTM D3039	Low-risk and pipe	Tension (high modulus and continuous fibers)
Engineering Properties	ASTM D638	Low-risk and pipe	Tension (low modulus and discrete fibers)
Engineering Properties	ASTM D2105	Pipe	Tension
Engineering Properties	ASTM D695	Low-risk and pipe	Compression (all shapes)
Engineering Properties	ASTM D6641	Low-risk and pipe	Compression (flat panels)
Engineering Properties	ASTM D790	Low-risk and pipe	Flexure (prepared or cut from sample)
Engineering Properties	ASTM D7294	Low-risk and pipe	Flexure (flat panels)

Exposure Category	Standard Designation	Composite Category	Test Condition
Engineering Properties	ASTM D3518	Low-risk and pipe	In-plane shear (tension)
Engineering Properties	ASTM D5379	Low-risk and pipe	Shear
Engineering Properties	ASTM D2344	Low-risk and pipe	Shear (short-beam)
Engineering Properties	ASTM D2412	Pipe	Stiffness
Engineering Properties	ASTM D2240	All	Hardness (Durometer – low modulus)
Engineering Properties	ASTM D2583	All	Hardness (Barcol – high modulus)
Engineering Properties	ASTM D1599	Pipe	Internal pressure
Engineering Properties	ASTM D4541	Coatings	Pull-off strength
Engineering Properties	ASTM C633	Coatings	Adhesion
Engineering Properties	ASTM D696	All	Thermal expansion
Deformation	ASTM D2992	Pipe	Fatigue
Deformation	ASTM D2990	All	Creep

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Keywords: composites, testing, accelerated testing

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Appendix A. Listing of Composite Materials Test Procedures

Composite Material Tests Table

Category	Standard Designation	Material Tested	Exposure Condition	ASTM C582 (1)	ASTM D4762 (2)	ASTM D1654 (3)	3M (4)	ARC (5)	Belzona (6)	Clock Spring (7)	Extreme Coatings (8)	FYFE (9)	Hardtide (10)	Metal Coatings (11)	Powercrete (12)	Reclamation (13)	AASHTO M306 (14)	ANSI ASC A14 (15)	ASTM D3299 (16)	ASTM D3753 (17)	ASTM D3982 (18)	ASTM D4024 (19)	ASTM D4097 (20)	ASTM D4167 (21)	Caltrans (22)	EJ Co (23)	Fibergrate (24)	Plasti-fab (25)	Strongwell (26)	USACE (27)	VPC (28)	ASTM D2992 (29)	ASTM D2996 (30)	ASTM D2997 (31)	ASTM D2262 (32)	ASTM D3350 (33)	ASTM D3517 (34)	ASTM D3754 (35)	ASTM D4161 (36)	ASTM D5421 (37)	ASTM D5685 (28)	ASTM D5813 (39)	ASTM D6041 (40)	ASTM F1173 (41)	ASTM F2720 (42)	AWWA C950 (43)	AWWA M45 (44)	Enduro (45)	Fiber Glass Systems (46)	Flowtite (47)
				General			Coatings										Low Risk Infrastructure															Pipelines																				
							Specifications										Specifications										Manufacturers					Specifications																	Manufacture		
Construction	ASTM D2657	Polyolefin	Joining (heat fusion)																																								42					
Construction	ASTM D2774	Plastic	Underground installation (pressure pipe)																																								42					
Construction	ASTM F1290	Polyolefin	Joining (electrofusion)																																								42					
Construction	ASTM F1668	Plastic	Burial																																								42					
Corrosion/Chemical Attack	ASTM C581	FRP	Any potential reagent or solution	1	2										12			16	17	18		20																35					40							
Corrosion/Chemical Attack	ASTM D1654	Painted/Coated substrates	Evaluation of corrosion sample																																														
Corrosion/Chemical Attack	ASTM D2803	Organic coatings on metal	Filiform corrosion			3																																											
Corrosion/Chemical Attack	ASTM D3681	FRP pipe	Any potential reagent or solution	1																														32			35					39	40		43				47
Corrosion/Chemical Attack	ASTM D543	Plastics	50 different reagents		2																																					39							
Corrosion/Chemical Attack	ASTM D7705	FRP bar in concrete	Alkali resistance																																													
Corrosion/Chemical Attack	ASTM G39	Coatings	Bent beam										10																																				
Corrosion/Chemical Attack	ASTM G8	Coatings, pipeline	Disbonding						6						12																																		
Creep/Fatigue	ASTM C394	Sandwich Core	Shear fatigue																																													
Creep/Fatigue	ASTM D1598	Plastic	Time to failure, internal pressure, fatigue																													29	30	31						38			41	42					
Creep/Fatigue	ASTM D2143	FRP	Internal pressure fatigue																													29	30	31															
Creep/Fatigue	ASTM D2412	Plastics	Stiffness																																													
Creep/Fatigue	ASTM D2837	Plastic	Hydrostatic/pressure design																																								42					
Creep/Fatigue	ASTM D2990	Plastics	Tension, compression and flexure creep		2																																											47
Creep/Fatigue	ASTM D2992	FRP	Hydrostatic/pressure design																														30	31	32		34	35					41		43		46		
Creep/Fatigue	ASTM D3479	FRP	Tension fatigue		2																																											
Creep/Fatigue	ASTM D5365	FRP	Strain																																								42					
Creep/Fatigue	ASTM D6115	FRP	Tension fatigue		2																																										
Creep/Fatigue	ASTM D671	Plastics	Flexural fatigue, constant amplitude force		2																																										
Creep/Fatigue	ASTM D7337	FRP	Tensile creep rupture		2																																										
Creep/Fatigue	ASTM D7615	FRP	Open-hole fatigue response		2																																										
Creep/Fatigue	EN 1227:1997[1]	GRP	Ring deflection under wet conditions																																													
Creep/Fatigue	ISO 7684	FRP	Creep																																													
Electrical	ASTM D149	Solid insulating materials	Voltage and dielectric strength						6		8			11	12																																		
Electrical	ASTM D150	Solid insulating materials	AC loss characteristics and permittivity						6																																								45		
Electrical	ASTM D495	Solid insulating materials	High-voltage, low-current, dry arc resistance								8																																						
Fire	ASTM D648	Plastics	Heat distortion temperature		2		4		6																																								
Fire	ASTM E1529[1]	All	Hydrocarbon pool fire effects																																								41					
Fire	ASTM E84	Building materials	Surface burning	1																																	24		26								45		
Fire	ISO 11357	Coatings	Heat resistance						6																																							
Fire	ASTM D635	Plastics	Rate and time of burning																																		24		26								45		
Freeze/thaw	ASTM C666	Concrete	Freeze/thaw or Freeze/thaw/moisture																																													
Hygrothermic	ASTM C1560	FRP bar in concrete	Moisture and Temperature change																																													
Hygrothermic	ASTM D1151	Adhesive bonding	Moisture and Temperature change																																												
Impact/Erosion/Abrasion/Cavitation	ASTM C501	Ceramic (unglazed)	Abrasion (Taber abraser)																							23																								
Impact/Erosion/Abrasion/Cavitation	ASTM D1822	Plastics and electrical insulating	Tensile-impact energy		2																																											
Impact/Erosion/Abrasion/Cavitation	ASTM D2444	Thermoplastic pipe	Impact																																													
Impact/Erosion/Abrasion/Cavitation	ASTM D256	Plastics	Izod impact		2		4		6			9																																				
Impact/Erosion/Abrasion/Cavitation	ASTM D2794	Organic coatings	Impact					5						11																																			
Impact/Erosion/Abrasion/Cavitation	ASTM D4060	Coatings	Abrasion (Taber abraser)				4	5	6					11	12																																		
Impact/Erosion/Abrasion/Cavitation	ASTM D6264	FRP	Damage resistance, concentrated indentation		2																																											
Impact/Erosion/Abrasion/Cavitation	ASTM D7136	FRP	Damage resistance, drop-weight impact		2																																											
Impact/Erosion/Abrasion/Cavitation	ASTM D7137	FRP	Compression residual		2																																											
Impact/Erosion/Abrasion/Cavitation	ASTM D968	Coatings	Abrasion (falling abrasive)																																													
Impact/Erosion/Abrasion/Cavitation	ASTM G134	Solid materials	Cavitation													13																																	
Impact/Erosion/Abrasion/Cavitation	ASTM G14	Coatings, pipeline	Impact, falling weight test												12																																		
Impact/Erosion/Abrasion/Cavitation	ASTM G195	All	Abrasion (rotary platform abraser)																																													
Impact/Erosion/Abrasion/Cavitation	ASTM G32	All	Cavitation																																													
Impact/Erosion/Abrasion/Cavitation	ASTM G65	Coatings, metallic	Abrasion, dry sand/rubber wheel								8		10																																			
Impact/Erosion/Abrasion/Cavitation	ASTM G77	All	Abrasion, block on ring								8																																						
Impact/Erosion/Abrasion/Cavitation	DIN 19565	FRP pipe	Abrasion																																													47
Mechanical Properties/Performance	ASTM C1028	Ceramic and other like surfaces	Static coefficient of friction																							23																								
Mechanical Properties/Performance	ASTM C307	Mortar, grout (chemical-resistant)	Tension					5																																								
Mechanical Properties/Performance	ASTM C579	Mortar, grout (chemical-resistant)	Compressive					5																																								
Mechanical Properties/Performance	ASTM C580	Mortar, grout (chemical-resistant)	Flexure					5																																								
Mechanical Properties/Performance	ASTM C6272	FRP	Flexural properties, four-point bending		2																																											
Mechanical Properties/Performance	ASTM C633	Coatings, spray	Adhesion										10																																			
Mechanical Properties/Performance	ASTM C78	FRP (strengthening)	Beam bond																																													
Mechanical Properties/Performance	ASTM D1002	Adhesive bonding	Metal to metal				4		6																																							
Mechanical Properties/Performance	ASTM D1505	Plastics	Density (density-gradient technique)		2																																						42					

Composite Material Tests Table

Category	Standard Designation	Material Tested	Exposure Condition	ASTM C582 (1)	ASTM D4762 (2)	ASTM D1654 (3)	3M (4)	ARC (5)	Belzona (6)	Clock Spring (7)	Extreme Coatings (8)	FYFE (9)	Hardtide (10)	Metal Coatings (11)	Powercrete (12)	Reclamation (13)	AASHTO M306 (14)	ANSI ASC A14 (15)	ASTM D3299 (16)	ASTM D3753 (17)	ASTM D3982 (18)	ASTM D4024 (19)	ASTM D4097 (20)	ASTM D4167 (21)	Caltrans (22)	EJ Co (23)	Fibergrate (24)	Plasti-fab (25)	Strongwell (26)	USACE (27)	VPC (28)	ASTM D2992 (29)	ASTM D2996 (30)	ASTM D2997 (31)	ASTM D2262 (32)	ASTM D3350 (33)	ASTM D3517 (34)	ASTM D3754 (35)	ASTM D4161 (36)	ASTM D5421 (37)	ASTM D5685 (28)	ASTM D5813 (39)	ASTM D6041 (40)	ASTM F1173 (41)	ASTM F2720 (42)	AWWA C950 (43)	AWWA M45 (44)	Enduro (45)	Fiber Glass Systems (46)	Flowtite (47)
				General			Coatings										Low Risk Infrastructure															Pipelines																				
							Specifications										Specifications										Manufacturers					Specifications																	Manufacture		
Mechanical Properties/Performance	ASTM D1599	Plastics	Hydraulic pressure															16			19										29	30	31						37	38		40	41		43			46		
Mechanical Properties/Performance	ASTM D2105	FRP (pipe and tube)	Tension (longitudinal)																													30	31										41		43			46		
Mechanical Properties/Performance	ASTM D2122	Pipe and fittings	Dimensions																																								42							
Mechanical Properties/Performance	ASTM D2240	Rubber	Durometer hardness					5	6						12																																			
Mechanical Properties/Performance	ASTM D2290	Plastics and FRP	Hoop tension																																		34	35									43				
Mechanical Properties/Performance	ASTM D2344	FRP	Short-beam strength		2																							26	27																					
Mechanical Properties/Performance	ASTM D2412	Plastics (pipe)	Stiffness																17													30	31	32		34	35								43			46	47	
Mechanical Properties/Performance	ASTM D2583	Plastics	Indentation hardness	1	2		4		6		8	9						16	17	18		20						25	26		28																			
Mechanical Properties/Performance	ASTM D2924	FRP	Buckling, compression, leaking																																								41							
Mechanical Properties/Performance	ASTM D2925	FRP	Deflection (water load)																																													46		
Mechanical Properties/Performance	ASTM D3039	FRP	Tension		2					7		9																26	27														39							47
Mechanical Properties/Performance	ASTM D3410	FRP	Compressive, shear loading		2																																													
Mechanical Properties/Performance	ASTM D3418	FRP	Transition temperature, DSC		2																																												
Mechanical Properties/Performance	ASTM D3518	FRP	In-plane shear		2																								27																				
Mechanical Properties/Performance	ASTM D3567	FRP (pipe)	Dimensions																												29	30	31	32		34	35			38	39	40	41		43					
Mechanical Properties/Performance	ASTM D3846	Plastics (reinforced)	Shear		2																																												
Mechanical Properties/Performance	ASTM D3895	Polyolefin	Oxidative-induction time, DSC																																							42							
Mechanical Properties/Performance	ASTM D4255	FRP	In-plane shear, rail shear method		2																																												
Mechanical Properties/Performance	ASTM D4385	FRP	Visual defects																									26																					
Mechanical Properties/Performance	ASTM D4541	Coatings	Pull-off strength					5	6					11	12																																			
Mechanical Properties/Performance	ASTM D5083	FRP	Tensile properties, straight-sided specimens		2																																												
Mechanical Properties/Performance	ASTM D5379	Composite	V-notch shear		2																							26																					
Mechanical Properties/Performance	ASTM D5448	FRP cylinders	Inplane shear		2																																												
Mechanical Properties/Performance	ASTM D5449	FRP cylinders	Transverse compression		2																																												
Mechanical Properties/Performance	ASTM D5450	FRP cylinders	Transverse tension		2																																												
Mechanical Properties/Performance	ASTM D5528	FRP	Interlaminar fracture toughness, mode I		2																																												
Mechanical Properties/Performance	ASTM D5766	FRP	Tension, open-hole		2																																												
Mechanical Properties/Performance	ASTM D5961	FRP	Bearing response		2																																												
Mechanical Properties/Performance	ASTM D610	Steel	Rusting			3																																												
Mechanical Properties/Performance	ASTM D618	Plastic	Conditioning for testing		2													16			19	20									29	30	31		33				38		40		42							
Mechanical Properties/Performance	ASTM D638	Plastics	Tension	1	2		4	5	6													20						25	26	27			30		32	33	34	35			39	40		42	43		45	46	47
Mechanical Properties/Performance	ASTM D6415	FRP	Curved-beam strength		2																																												
Mechanical Properties/Performance	ASTM D6484	FRP	Compressive strength, open-hole		2																																												
Mechanical Properties/Performance	ASTM D6641	FRP	Compression/shear		2																							26																					
Mechanical Properties/Performance	ASTM D6671	FRP	Interlaminar fracture toughness, mixed mode		2																																												
Mechanical Properties/Performance	ASTM D6742	FRP	Tension/compression, filled-hole		2																																												
Mechanical Properties/Performance	ASTM D695	Plastics	Compressive	1	2		4	5	6										17									25	26	27					32		34	35			39				43		45	46	47
Mechanical Properties/Performance	ASTM D696	Plastics	Thermal expansion		2							9																25	26																			46		
Mechanical Properties/Performance	ASTM D7028	FRP	Transition temperature, DMA		2																																												
Mechanical Properties/Performance	ASTM D7078	Composite	Shear properties, v-notched rail method		2																																												
Mechanical Properties/Performance	ASTM D7087	Coated metal	Rust Creepage			3																																											
Mechanical Properties/Performance	ASTM D714	Paint	Blistering			3																																											
Mechanical Properties/Performance	ASTM D7205	FRP bar	Tension		2																																												
Mechanical Properties/Performance	ASTM D7248	FRP	Bearing/bypass interaction response		2																																												
Mechanical Properties/Performance	ASTM D7264	FRP	Flexure		2																								27																				
Mechanical Properties/Performance	ASTM D7291	FRP	Tensile strength, through-thickness flatwise		2																																												
Mechanical Properties/Performance	ASTM D7332	FRP	Pull-through resistance		2																																												
Mechanical Properties/Performance	ASTM D7522	FRP (strengthening)	Pull-off strength		2																								27																				
Mechanical Properties/Performance	ASTM D7565	FRP (strengthening)	Tension		2																																												
Mechanical Properties/Performance	ASTM D7616	FRP (strengthening)	Splice shear strength properties		2																																												
Mechanical Properties/Performance	ASTM D7617	FRP	Transverse shear strength		2																																												
Mechanical Properties/Performance	ASTM D785	Plastics	Rockwell hardness																17																																
Mechanical Properties/Performance	ASTM D790	Plastics	Flexure	1	2		4	5	6			9							17			20						25	26	27	28				32		34	35			39			42			45		
Mechanical Properties/Performance	ASTM D792	Plastics	Density (by displacement)		2																							25	26															42			45	46	
Mechanical Properties/Performance	ASTM D953	Plastics	Bearing strength		2																							26																					
Mechanical Properties/Performance	ASTM E1922	FRP	Translaminar fracture toughness		2																																												
Mechanical Properties/Performance	ASTM F948	Plastic piping	Time to failure, internal pressure with flow																																														
Moisture Absorbtion	ASTM D5229	FRP	Moisture		2																																												
Moisture Absorbtion	ASTM D570	Plastics	Immersion		2							9			12													25	26																			45		
Quality Control	ASTM C613	Composite	Constituent content		2																																												
Quality Control	ASTM D2471[1]	Resins	Gel time and peak exothermic temperature		2																																												
Quality Control	ASTM D2563	FRP	Visual defects																				21					25																					
Quality Control	ASTM D2584	FRP	Fiber and resin content	1	2													16	17	18		20						25							32		34	35					40	41					
Quality Control	ASTM D2734	FRP	Void content		2																																												

Composite Material Tests Table

Category	Standard Designation	Material Tested	Exposure Condition	ASTM C582 (1)	ASTM D4762 (2)	ASTM D1654 (3)	3M (4)	ARC (5)	Belzona (6)	Clock Spring (7)	Extreme Coatings (8)	FYFE (9)	Hardtide (10)	Metal Coatings (11)	Powercrete (12)	Reclamation (13)	AASHTO M306 (14)	ANSI ASC A14 (15)	ASTM D3299 (16)	ASTM D3753 (17)	ASTM D3982 (18)	ASTM D4024 (19)	ASTM D4097 (20)	ASTM D4167 (21)	Caltrans (22)	EJ Co (23)	Fibergrate (24)	Plasti-fab (25)	Strongwell (26)	USACE (27)	VPC (28)	ASTM D2992 (29)	ASTM D2996 (30)	ASTM D2997 (31)	ASTM D3262 (32)	ASTM D3350 (33)	ASTM D3517 (34)	ASTM D3754 (35)	ASTM D4161 (36)	ASTM D5421 (37)	ASTM D5685 (28)	ASTM D5813 (39)	ASTM D6041 (40)	ASTM F1173 (41)	ASTM F2720 (42)	AWWA C950 (43)	AWWA M45 (44)	Enduro (45)	Fiber Glass Systems (46)	Flowtite (47)
				General		Coatings											Low Risk Infrastructure														Pipelines																				
						Specifications																					Manufacturers																							
Quality Control	ASTM D3171	Composite	Constituent content	2																									27																				
Rehabilitation	ASTM F1216	Pipelines and conduits	Resin-impregnated tube																																							39								
Rehabilitation	ASTM F1743	Pipelines and conduits	CIPP																																							39								
Rehabilitation	ASTM F2019	Pipelines and conduits	GRP CIPP																																							39								
Safety	OSHA 1910.23	All	Railings																										26																				
Safety	OSHA 1910.27	All	Ladders																									25	26																				
Specification	AASHTO M306	All	Drainage, sewer, utility, and related castings																						23																									
Specification	ASTM C582	FRP	Corrosion resistant elements															16		18		20	21																	37			40								
Specification	ASTM D2150	Glass fabric	for FRP															16				20																												
Specification	ASTM D2996	FRP	Pipe, filament-wound															16				20																	37										45	46	
Specification	ASTM D2997	FRP	Pipe, centrifugally cast															16				20																	37											46	
Specification	ASTM D3262	FRP	Sewer (gravity)																																				37												47
Specification	ASTM D3299	FRP	Tanks, filament-wound (corrosion resistant)																																		37										45		
Specification	ASTM D3350	Plastics	Pipe and fittings (polyethylene)																																										42				
Specification	ASTM D3517	FRP	Pipe (pressure), buried (8 to 156 in)																																		37								43				47
Specification	ASTM D3753	FRP	Manholes and wetwells																									25																					
Specification	ASTM D3754	FRP	Sewer and pressure pipe																																		37												47
Specification	ASTM D3982	FRP	Ducts, contact-molded																																		37												
Specification	ASTM D4024	FRP	Flanges, machine made															16				20														33					38							46	
Specification	ASTM D4097	FRP	Tanks, contact-molded (corrosion resistant)																																		37										45		
Specification	ASTM D4161	FRP	Pipe joints																															32		34	35											
Specification	ASTM D4167	FRP	Fans and blowers																																										43				
Specification	ASTM D4357[1]	Plastic	Laminates																																													
Specification	ASTM D5421	FRP	Flanges, contact molded															16				19	20																				40							
Specification	ASTM D5685	FRP	Fittings																																														
Specification	ASTM D5686[1]	FRP	Fittings																																									41					
Specification	ASTM D5813	FRP	Pipes, rehabiliting																																													
Specification	ASTM D6041	FRP	Pipe, contact-molded (corrosion resistant)																																													
Specification	ASTM F1173	FRP	Pipe, marine																																													
Specification	ASTM F2720	FRP	Pipe (spiral wound, large diameter)																																												
Specification	AWWA C950	FRP	Pipe																																												
Specification	AWWA M45	FRP	Pipe, design																																												
Temperature Cycles	ASTM D3045	Plastics	Heat aging																																												
UV	ASTM D1499	Plastics	Open-flame carbon-arc																																												
UV	ASTM D2565	Plastics	Xenon-arc																										26																				
UV	ASTM D4329	Plastics	Fluorescent UV Lamp																																												
UV	ASTM D4364	Plastics	Concentrated Sunlight																																												
UV	ASTM D4587	Painted/Coated substrates	Fluorescent UV Lamp			3										13																																47
UV	ASTM D5031	Painted/Coated substrates	Enclosed carbon-arc																																												
UV	ASTM D6360	Plastics	Enclosed carbon-arc																																											
UV	ASTM D6695	Painted/Coated substrates	Xenon-arc			3																																								
UV	ASTM D822	Painted/Coated substrates	Open-flame carbon-arc			3																																								
UV	ASTM G151	Nonmetallic	Laboratory light sources																																												
UV	ASTM G154	Nonmetallic	Fluorescent UV Lamp																						22																								
Water quality	NSF/ANSI Standard 61	All	Health effects																																								42					
Weathering	ASTM B117	All	Salt spray operation			3	4		6				10	11																																		
Weathering	ASTM D1014	Paints and coatings on metal	Outdoor exposure			3																																								
Weathering	ASTM D1735	Coatings	Water resistance (fog apparatus)			3																																								
Weathering	ASTM D2247	Coatings	Water resistance (100% humidity)			3																																								
Weathering	ASTM D4141	Coatings	Sunlight exposure			3																																								
Weathering	ASTM D4585	Coatings	Water resistance (controlled condensation)			3																																								
Weathering	ASTM D5894	Painted metal	Salt spray and UV exposure			3								11																																		
Weathering	ASTM D870	Coatings	Water resistance			3																																								
Weathering	ASTM G7	Nonmetallic	Atmospheric (natural)																																											
Weathering	ASTM G85	Coatings and metals	Salt spray (modified)			3																																								
Weathering	ASTM G87	Coatings and metals	Sulfur dioxide			3																																								
Weathering	ASTM G90	Nonmetallic	Concentrated Sunlight																																											

[1]Withdrawn

Composite Material Tests Table References

Number	Standard/Manufacturer	Title
1	ASTM C582	Standard Specification for Contact-Molded Reinforced Thermosetting Plastic (RTP) Laminates for Corrosion-Resistant Equipment
2	ASTM D4762	Standard Guide for Testing Polymer Matrix Composite Materials
3	ASTM D5421	Specification for Contact Molded Fiberglass (Glass-Fiber-Reinforced Thermosetting Resin) Flanges
4	ASTM D6041	Standard Specification for Contact-Molded “Fiberglass” (Glass-Fiber-Reinforced Thermosetting Resin) Corrosion Resistant Pipe and Fittings
5	ASTM D2992	Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings
6	ASTM D2996	Standard Specification for Filament-Wound “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe
7	ASTM D2997	Standard Specification for Centrifugally Cast “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe
8	ASTM D3262	Standard Specification for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer Pipe
9	ASTM D3350	Standard Specification for Polyethylene Plastics Pipe and Fittings Materials
10	ASTM D3517	Standard Specification for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pressure Pipe
11	ASTM D3754	Standard Specification for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer and Industrial Pressure Pipe
12	ASTM D4161	Specification for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe Joints Using Flexible Elastomeric Seals
13	ASTM D5685	Specification for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pressure Pipe Fittings
14	ASTM D5813	Standard Specification for Cured-In-Place Thermosetting Resin Sewer Piping Systems
15	ASTM F1173	Standard Specification for Thermosetting Resin Fiberglass Pipe Systems to Be Used for Marine Applications
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32	ASTM D3753	Standard Specification for Glass-Fiber-Reinforced Polyester Manholes and Wetwells
33	ASTM D3982	Standard Specification for Contact Molded “Fiberglass” (Glass Fiber Reinforced Thermosetting Resin) Ducts
34	ASTM D4024	Standard Specification for Machine Made “Fiberglass” (Glass-Fiber-Reinforced Thermosetting Resin) Flanges
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