Glass Fiber Reinforcement Chemical Resistance Guide

For the Selection of Glass Fiber Reinforcements in Fiber Reinforced Polymer (FRP) for Corrosive Environments

OCV™ Reinforcements | OCV™ Technical Fabrics | OCV™ Non-Woven Technologies

EDITION 1A

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For the latest edition visit the Owens Corning Advantex® glass website:
www.owenscorning.com/composites/aboutAdvantex.asp

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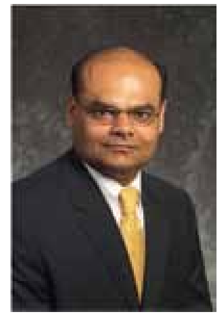
Foreword:



It is a pleasure to present this first-ever corrosion-resistance guide for glass fibers, developed to help end-users, engineers and fabricators select the optimum reinforcement for use in a fiberglass-reinforced polymer (FRP) application facing a corrosive environment.

Glass fiber reinforcements play a critical role in the performance of an FRP application in corrosive environments. As a result, the choice of glass reinforcement is a key factor in corrosion performance lowering the risk of failure.

Owens Corning is in a unique position to present this guide because of our material science competencies in corrosion and glass and surface chemistry. These competencies have allowed Owens Corning to invent most of the glass fiber types used today in FRP. We are now providing this tool – based on science, laboratory tests and field experience – to help you balance cost and performance in the selection of the best performing glass fiber for use in corrosive environments.

With more than 50 years of field experience, fiberglass-reinforced polymer (FRP) is proven technology for fighting corrosion. Tanks and pipe constructed with corrosion-resistant composites have consistently provided extended service life over those made with metals and FRP is now used regularly to replace expensive stainless steel and high-nickel alloys.

Building on this record of success, FRP composites are expected to perform in tougher environments today. There is a proliferation of applications where special corrosion-resistant properties are required, such as equipment for pollution control, mining, chemical processing, power plants and a variety of saltwater marine applications including tidal energy installations.

You can expect updates to this guide as more data are developed and analyzed and Owens Corning continues to advance the science of FRP composites and transform the materials world with advanced solutions.

Dr. Ashish Diwanji
Vice President, Innovation
Composites Group

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INTRODUCTION

Selecting the proper glass fiber type (composition) is critical to provide the longest life and reduce the risk of failure in fiberglass reinforced polymer (FRP) applications. There are now many types of glass fiber reinforcements in the marketplace. Owens Corning is providing this tool to help you select the best performing glass fiber for use in corrosive environments taking cost and performance into consideration.

From the beginning, Owens Corning has been the primary inventor of new glass fiber innovations to the market. The table below describes the historical evolution of glass fiber composition over time.

Glass Fiber Types Used In Composites Today Include

Glass Type	Year Invented	Key Attribute	Strength	Price	Inventor
A-Glass	1938	Insulation	Low	$	Owens Corning
E-Glass	1939	Electrical Grade	Moderate	$	Owens Corning
C-Glass	1943	Corrosion Resistant	Low	$	Owens Corning
R-Glass	1965	High Strength	High	$$	Saint-Gobain[1]
S-Glass	1965	High Strength	Very High	$$$	Owens Corning
AR-Glass	1974	Alkali Resistant	Low	$$	Owens Corning
E-CR Glass	1980	Corrosion Resistant	Moderate	$	Owens Corning
Advantex® Glass	1996	Corrosion Resistant	Moderate	$	Owens Corning
H-Glass	2004	High Stiffness	Moderate	$$	Saint-Gobain[1]
HPG[2]	2004	High Strength	High	$$	Owens Corning
Direct Melt-S	2008	High Strength/Stiffness	Very High	$$$	Owens Corning

1 – Owens Corning acquired the glass fiber reinforcements and technical fabrics businesses of Saint-Gobain in November 2007.
2 – HPG is an acronym for High-Performance Glass fibers

THE ROLE GLASS FIBER REINFORCEMENTS PLAY IN FRP APPLICATIONS

- Provides the mechanical structure (strength and stiffness) required in the FRP application
- Glass type optimizes corrosion performance

It is general practice to utilize glass fiber in a corrosion barrier and in the structural portion. To optimize the FRP design and reduce risk, the correct glass type must be specified.

INDUSTRY STANDARDS RECOMMENDING GLASS TYPE FOR FRP IN CORROSIVE ENVIRONMENTS

A. ASTM Designation

D 578 Standard Specification for Glass Fiber Strands Section 4.2.4: "The nomenclature 'E-CR Glass' is used for **boron-free** modified E-glass compositions for **improved resistance to corrosion** by most acids."

B. International Standard

ISO 2078 – Designation: Section 4.1.1 Glass used: "One or several letters, to specify the glass used by the manufacturer (see table at right)."

- E-glass is good for "general purpose" applications where the environmental conditions are not a concern.
- E-CR is glass designed for use in acidic/ corrosive environments

Type	General Indications
E	For general purposes; good electrical properties
D	Good dielectric properties
A	High alkali content
C	Chemical resistance
S	High mechanical strength
R	High mechanical strength
AR	Alkali resistant
E-CR	For use in acid environments

(Source: ISO 2078)

WHY IS THE GLASS TYPE SELECTION CRITICAL IN CORROSIVE ENVIRONMENTS?

When a corrosive chemical does come in contact with a glass fiber, if the wrong glass fiber type is selected it can degrade the fiber and destroy the resin bond, resulting in a significant reduction in structural properties. In a corrosive environment, gaseous or liquid chemicals can reach glass fibers in the structural portion of a finished FRP application and cause premature failure by multiple means including:

- Poor curing
- Diffusion
- Osmosis
- Applied stress
- Embrittlement
- Micro-cracking
- Swelling
- Impact
- Thermal gradients
- Pressure gradients
- Time

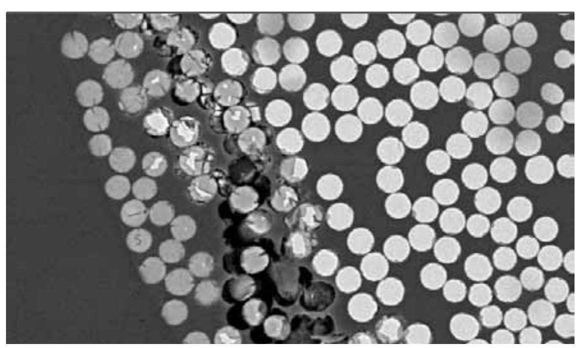


Figure 1 – A microscopic picture of pultruded **E-glass** fibers attacked in an FRP rod exposed to sulfuric acid after one month. The acid has penetrated through the composite laminate. White circles are individual E-glass fibers and the dark area is resin. In a similar study using Advantex® glass, the glass did not deteriorate from the attack even after six months of exposure.

NOTE: For more details about this subject visit our Advantex® website and download the white paper titled "An Inside Look at Corrosion in Composite Laminates" by Kevin Spoo, March 2010. www.owenscorning.com/composites/aboutAdvantex.asp Also see the book titled "Ageing of Composites" edited by Rod Martin, 2008, section 17.4 – Types of degradation in fiber reinforced plastic.

FABRICATION PROCESSES WHERE GLASS FIBERS ARE USED


Photo source: Strongwell Corporation

Various types of glass fiber products like fabric, rovings, mat and veil are used to construct FRP parts. Most FRP applications used in corrosive environments (pipe, tanks, duct work and stack liners) are made using the filament winding and pultrusion processes and contain 60 to 70% glass fiber reinforcements by weight.

Selecting the right glass fiber product depends on the process being used, the mechanical properties required, the resin choice and the chemical environment that it will face. The photo shows a pultrusion process and illustrates the important role glass fiber plays in the structure.

OWENS CORNING'S SOLUTION FOR CORROSION: TAKE RISK OUT... PUT ADVANTEX® GLASS IN

Advantex® Glass Fiber Reinforcements Description

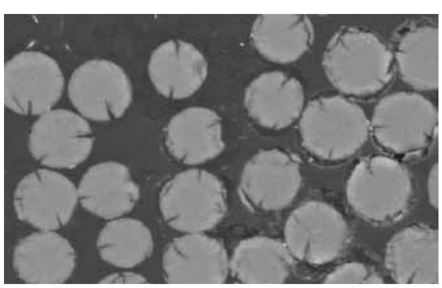
Advantex® glass is a patented **boron-free** glass formulation that is both a corrosion-resistant E-CR and E-glass fiber reinforcement meeting ASTM D 578 4.2.4 standard and is developed with the following attributes:

- Increased mechanical properties compared to standard E-glass and E-CR glasses
- Improved corrosion resistance compared to standard E-glass. Advantex® glass meets both ASTM D 578 4.2.4 and ISO 2078.

Advantex® Glass – Proven Performance in Corrosive Environments

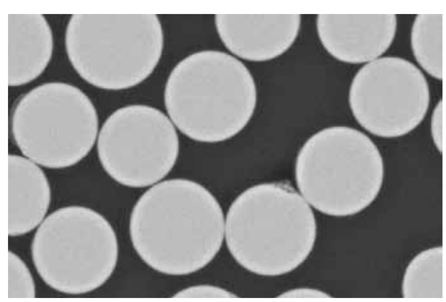
Performance in corrosive environments depends on the type of glass selected. The SEM (Scanning Electron Microscopy) photographs below show how composite rods respond to 10% sulfuric acid after three months. As shown, the E-glass breaks down and de-bonds from the resin matrix and, therefore, is an incorrectly specified glass for use in this corrosive environment. By comparison, the Advantex® glass shows no signs of deterioration and maintains its full strength.

E-Glass FRP Rod



E-glass starts to break down, with leaching and cracking causing de-bonding from the resin which could lead to the potential failure of the application.

Advantex® FRP Rod



Advantex® glass continues to perform after three months with no leaching, cracking or weakening. It maintains its strength in a corrosive environment.

OWENS CORNING OFFERS FULL LINE OF GLASS FIBER REINFORCEMENT PRODUCTS

When an FRP solution is selected as the material of choice for a corrosive environment, Owens Corning offers all the products necessary to provide long-lasting high-performance solutions. See the information below for details on our full range of products.

Product Offering by Glass Reinforcement Type

Glass Type	E-Glass	C-Glass	Advantex®	Cem-FIL® AR-Glass	HPG[3]-Glass (S, H, R)
Key Attribute	General Purpose	Corrosion Resistant	Corrosion Resistant	Alkali Resistant	High Strength
Available Products	Fabric	Veil	Direct Roving	Direct Roving	Direct Roving
	Assembled Roving[1]		Assembled Roving	Veil[2]	Fabric
	Direct Roving[1]		Fabric	Assembled Roving	
	Chopped Strands[1]		Veil CSM CFM Chopped Strands Milled Fiber		

1. Not available in all regions 2. Currently only available for specialty applications 3. High-performance glass fibers

ADVANTEX® GLASS PRODUCTS AND FUNCTION

Advantex® Glass Direct Roving/Single-End Roving/T30® Roving

Direct roving provides strength in most FRP applications in filament wound and pultruded processes for applications including pipe, tanks, structural I-beams, piling, grating and many other applications facing corrosion. Specifying Advantex® glass reduces the risk of structural failure due to its stability in corrosive environments.

Advantex® Glass Assembled/Multi-End Roving

Assembled rovings can be chopped and used in the corrosion barrier in place of chopped strand mat. They can also be used in the spray-up process to mold certain laminates used in corrosive environments.

Advantex® Glass Chopped Strand Mat (CSM)

CSM is often used as part of the corrosion barrier in FRP applications. CSM provides the strength required for outstanding performance in a variety of hand lay-up applications.

Advantex® Glass Continuous Filament Mat (CFM) – Unifilo® Mat

Continuous filament mat used in the pultrusion process provides the transversal resistance with high mechanical properties able to withstand corrosive environments.

Advantex® Glass, C-glass and AR-glass* Veil

Non-woven veils strengthen the resin-rich corrosion barrier of many applications and create a strong bond with the underlying laminate. Surfacing veils also isolate the structural fibers from exposure to abrasion and corrosion, contributing to the structural integrity of the total composite. The appropriate veil glass must be selected based on the type of corrosive environment

*Currently available for certain applications.

Advantex® Glass Technical Fabrics

OCV™ Technical Fabrics provide high-quality fabrics designed to meet your performance requirements in corrosive environments. Whether the need is woven roving, multiaxial, unidirectional or a combination, OCV™ Technical Fabrics can provide the Advantex® glass solution. Owens Corning manufactures fabrics using many kinds of glass types for input. If the application is for a corrosive environment, specify Advantex® glass fibers as the input.

Owens Corning High-Performance Glass Fiber Reinforcements (S, H, R)

The OCV™ High-Performance Reinforcement platform features ShieldStrand,® XStrand,® FliteStrand® and WindStrand® high-strength reinforcement products targeted at industrial, ballistic, aerospace and wind energy markets. These products provide superior corrosion resistance and mechanical properties and should be considered in highly demanding FRP applications. Please contact Owens Corning for additional information by selecting the email address or phone number below.

Owens Corning Cem-FIL® AR Glass Fiber Reinforcements

Cem-FIL® alkali-resistant (AR) glass fibers have been in use for 40 years in more than 100 countries to create some of the world's most stunning architecture while offering strong and durable performance in widely varying cement- and mortar-based applications. Cem-FiL® AR glass provides superior corrosion resistance in certain chemical and high-alkaline environments. Please contact Owens Corning for additional information by selecting the email address or phone number below.

NOTE: Please contact Owens Corning for additional information by selecting the appropriate email address or phone number of the region where you are located.

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WRITING A SPECIFICATION FOR FRP STRUCTURES USED IN CORROSIVE ENVIRONMENTS

When using glass fiber reinforcements it is necessary to specify the proper glass fibers for the **structural portion** and the **corrosion barrier**.

Structural Section of an FRP Application

The structural portion provides the vast majority of the mechanical makeup (strength and stiffness) of an FRP part. The results from chemical testing in this guide indicate that Advantex® glass shows the highest overall performance and is therefore recommended for specification in the structural portions. This is an example of a specification that can be used for a structural portion.

"Glass fiber reinforcements shall be Advantex® glass or equivalent meeting ASTM D 578-00 section 4.2.4. This glass will have sizing compatible with the resin specified."

Corrosion Barrier of an FRP Application

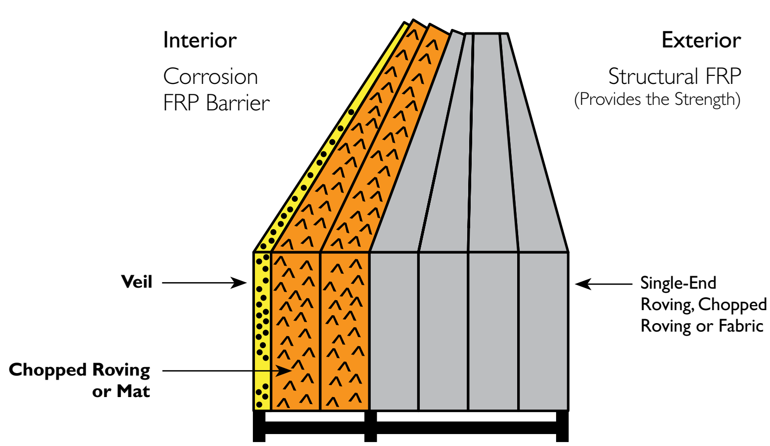
The corrosion barrier normally does not supply any structural strength and is used to help slow the diffusion of the corrosive media through the laminate. This section of the FRP laminate is normally made up of an inner surface veil and the remainder consisting of a mat (either made up of chopped strand mat or chopped roving). It's important to specify the proper veil, independent of the mat specification to ensure the highest level of corrosion resistance. The illustration depicts an example of an FRP part showing the corrosion barrier and structural portion.

The veil portion is the inner surface of the corrosion barrier and may require another material like glass, carbon or polyester depending on the corrosive chemical environment. When a glass veil has been selected, use this guide to identify the appropriate glass type for the specific chemical environment or contact Owens Corning for a recommendation.

When a mat section is also included in the design of a corrosion barrier based on the test results found in this guide, it is likely that Advantex® glass should be the reinforcement specified. The specification below can be used for that segment of the corrosion barrier.

"Glass fiber reinforcements shall be Advantex® glass or equivalent meeting ASTM D 578-00 section 4.2.4. This glass will have sizing compatible with the resin specified."

Filament Winding or Laminate
(example: pipe, tank, ducting, etc.)



OWENS CORNING GLASS FIBER TYPE SPECIFICATION REQUEST FORM

If you have questions not answered in this guide, or would like to have a recommendation for the glass type to use in a specific situation, you can contact Owens Corning in two ways:

1. Complete and submit the online format at: www.owenscorning.com/composites/aboutAdvantex.asp

2. Make a copy of this form and send, using the appropriate regional fax number listed below.

Fax Completed Form

Fax – Americas: 1.740.321.4607
Fax – Europe & MEA: +46.346.83733
Fax – Asia Pacific: +66.2.745.6961

Project Name: ______________________________

Date: ______________________________

Contact Information

Company: ______________________________ Country: ______________

Name: ______________________________

Email Address: ______________________ Phone: ______________________

FRP Part Information

Part Type (tank, pipe, scrubber, duct, etc.): ______________________________

Dimensions: ______________________ Capacity: ______________________

Industry (mining, chemical, power, etc.): ______________________________

Operating Conditions:

Chemical Type or Environment — Concentrations Normal

1. ______________________________ ______________
2. ______________________________ ______________
3. ______________________________ ______________
4. ______________________________ ______________

pH: Typical: ______________ Minimum: ______________ Maximum: ______________

GUIDE DESCRIPTION

The final section of this guide will help you identify the best glass fiber type to specify for various corrosive environments based on laboratory testing, showing the impact various chemicals will have on different glass fiber types.

Depending on the chemical, the guide provides a bare glass weight loss analysis exposed to specific chemical solutions. Bare glass testing may require further explanation. In those situations we will provide additional back-up information to support the selection of the best performing glass fiber type.

Owens Corning intends to update this guide as we continue to test other chemicals and the effects on glass fiber reinforcements. Please check the Advantex® glass website for new versions and additional information. www.owenscorning.com/composites/aboutAdvantex.asp

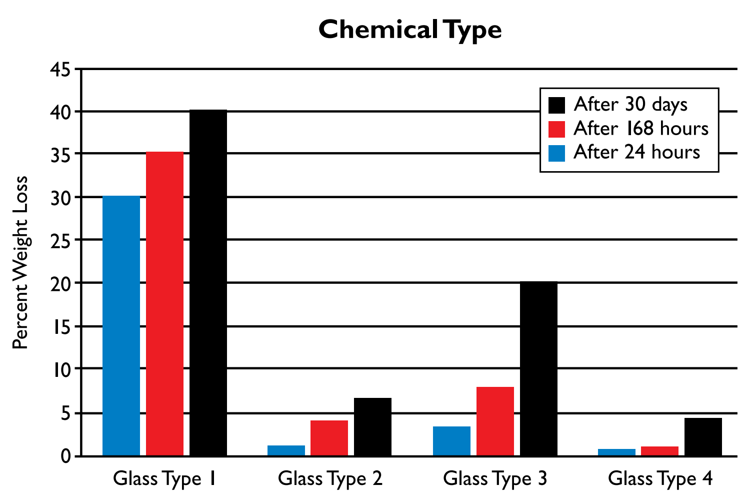
TEST METHODS AND INTERPRETATION OF RESULTS

Owens Corning uses several test methods to determine how various forms of glass fiber perform in corrosive environments. These methods include:

1. Bare Glass Weight Loss Testing

This is a test that compares the corrosion resistance of different glass types in a corrosive media. The Y-axis shows the percentage of elements leached from the glass fiber. A taller bar indicates a higher amount of weight loss and is a bad indicator. A shorter bar indicates better corrosion resistance. The X-axis lists various types of glass fiber composition.

There are multiple bars shown above a glass composition and these refer to the duration in time that the glass was exposed to the chemical media. Multiple time durations are shown because the rate of corrosion between glass compositions is hugely different in certain corrosive media. While weight loss testing is rapid, it can in certain circumstances underestimate differences between glass fiber types due to the formation of insoluble salts or re-deposition back onto the glass fibers. This results in highly leached glass fibers appearing not to lose as much weight as has actually been leached from the fiber. In the real world the corrosive media volume is very large compared to the amount of glass. Therefore, we have included several other in-depth techniques/analyses to assess the impact of corrosion in this document.

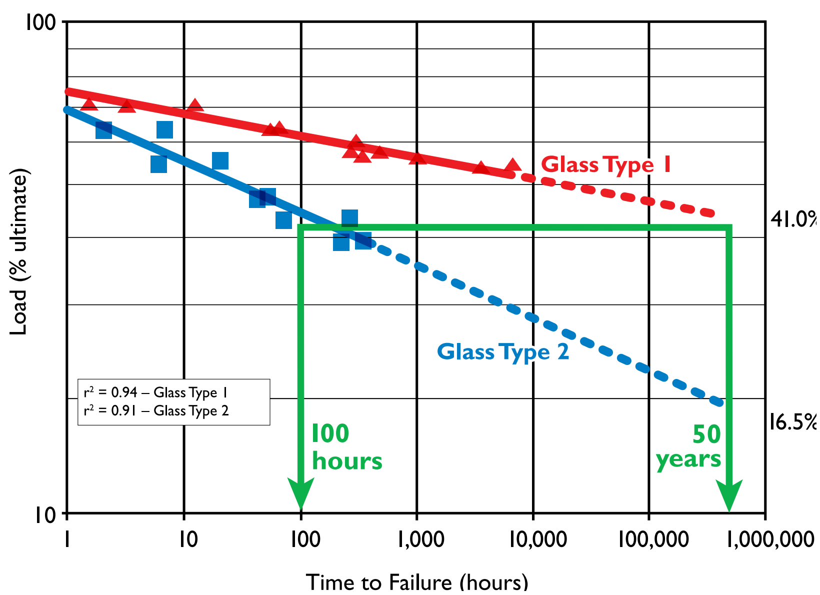


2. Stress Rupture Corrosion Tensile Testing of FRP Rods

Stress rupture corrosion testing comes the closest to incorporating the multiple issues (stress and corrosion) a structure might face. Based upon ASTM D2992 and ASTM D3681, this expensive and time-consuming method is really the "gold standard" of understanding how different glass types perform in a corrosive media independent of resin type or composite construction. Stress levels, either in percent ultimate stress or absolute stress in MPa, are plotted in a log-log chart on the Y-axis. The X-axis represents exposure time in hours. The glass fiber FRP rod with the flattest slope is least affected by the corrosive media.

To easily compare the differences between glass types find the 50-year Y-intercept of the flattest line and follow that stress level (example, 41.0%) horizontally back to the line representing the other glass type on the chart. Where that stress level (41.0% on the Y-axis) intercepts the other plotted line (100 hours) it estimates the length of time (read on the X-axis) that the FRP structure could withstand the 41.0% stress. In this example, Glass Type 1 can maintain 41% of its original ultimate stress for 50 years, while Glass Type 2 has degraded to that level within 100 hours.

Stress-Rupture Performance of Composite Rods in a Corrosive Media



3. Scanning Electron Microscopy (SEM)

SEM allows us to see on a microscopic scale what is happening to the FRP, including the glass fiber. This is where we see effects such as re-deposition, pitting, cracking, crystal growth or leaching when coupled with Energy Dispersive X-ray. SEM is used when inconsistencies arise between weight loss charts and previous published literature, performance in similar but not identical corrosive media or real-world experience. SEM helps us understand better why difference may or may not exist.

For a more detailed description of each method please see **Appendix A** of this guide.

SUMMARY OF RESULTS & GENERAL RECOMMENDATIONS

Below is a summary of which glass fiber types performed best across the general chemical categories. Details of performance for the specific results of the chemical testing are provided in the next section. Glass types tested include: E-glass, C-glass, Advantex® glass and AR-glass. FRP parts (like tanks, pipe, etc.) facing a corrosive environment normally have a corrosion barrier and a structural portion. If glass is selected as the reinforcement in either the corrosion barrier or structural portion, this summary shows which type of glass fiber is best suited for each area.

Guide Summary of the Highest Performing Glass Fiber Reinforcements by Corrosive Environment

Composite Laminate Section	Mineral Acids	Organic Acids	Deionized Water	Alkaline	Salts
Corrosion Barrier Recommended Inner Surface Veil*	AR-Glass or C-Glass	Advantex®	Advantex®	AR-Glass or Advantex®	AR-Glass or Advantex®
Corrosion Barrier Recommended Mat/ Chop Portion**	Advantex®	Advantex®	Advantex®	Advantex®	Advantex®
Structural Portion Recommended Fiber Type	Advantex®	Advantex®	Advantex®	Advantex®	Advantex®
Chemicals Tested	Sulfuric Hydrochloric Nitric Phosphoric Aqua Regia	Acetic Citric	Deionized Water Tap Water	Ammonium Hydroxide Sodium Hydroxide Sodium Chlorite Sodium Hypochlorite	Sodium Chloride Ferric Chloride

* When glass fiber is the selected material as a veil product. Be sure to look at individual chemical pages for specific glass type.
** When glass fiber is the selected material as the chopped strand mat or chopped assembled rovings products.
NOTE: AR-glass (Cem-FIL® glass) is only available in certain veil types for specialty applications.

For additional information,
recommendations or support please contact:

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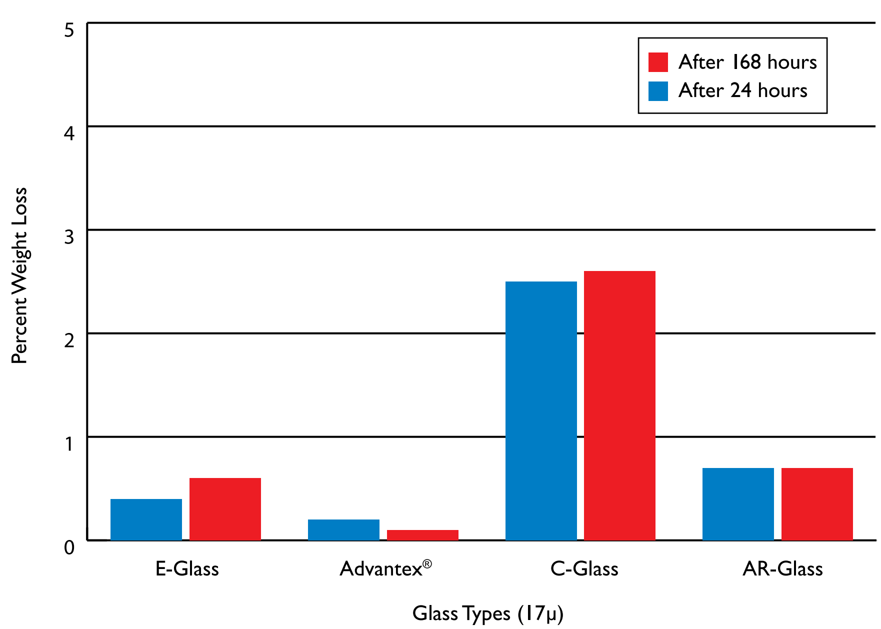
ACETIC ACID

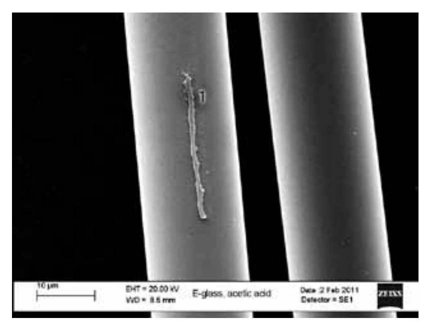
Bare Glass Weight Loss Testing: The weight loss testing in acetic acid appears to be minimal, but these numbers are deceptive. After further examination, we concluded that Advantex® glass had the best performance overall and would be the best choice for the entire corrosion barrier (as veil and mat) as well as the structural portion of an FRP part to ensure the highest performance.

The SEM photos of E-glass below show relatively unaffected fibers. However, an EDX (Energy Dispersive X-ray) analysis of the surfaces of all fibers shows a very uniform coating of a carbon containing salt of various leached elements from the glass. This coating appears on all fibers and adds weight to the fiber. The weight loss of leached elements in the glass exceeds the weight gain of the organic coating resulting in a net weight loss for all fibers, with C-glass affected the most. Although the relative performance of glass fibers in this study is probably indicative of their relative performance, the chart should not be interpreted that acetic acid weakly attacks glass fiber.

80% Acetic Acid @ 50°C



Scanning Electron Microscopy (SEM) Photos of E-glass:
The E-glass photo shows an area where two fibers were in contact with each other (Area 1 on SEM photo) and leachate accumulated between them. This coating and leachate added weight to these fibers making the bare glass weight loss testing appear less damaging than it really was.



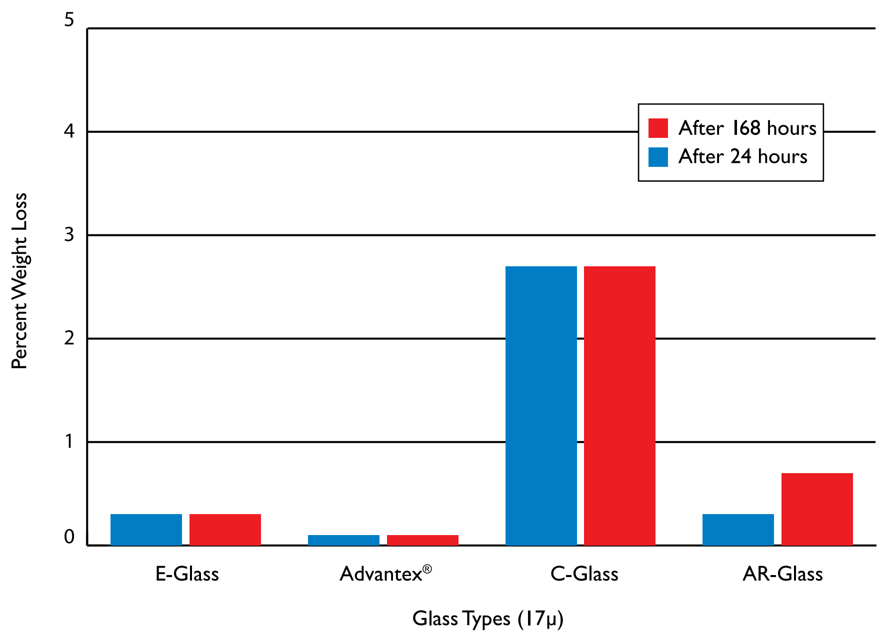
SEM photo of **E-glass** showing leachate accumulating on the glass fiber.

AMMONIUM HYDROXIDE

Glass Fiber Chemical Resistance

Bare Glass Weight Loss Testing: The results for ammonium hydroxide (high pH) show surprisingly little effect on Advantex® glass. However, C-glass is clearly attacked to a much greater extent than the other glass fibers. This testing suggests that Advantex® glass will perform better in the corrosion barrier (as the veil and mat) and structural portion. C-glass veil would not be the best choice for the corrosion barrier.

28% Ammonium Hydroxide @ 30°C

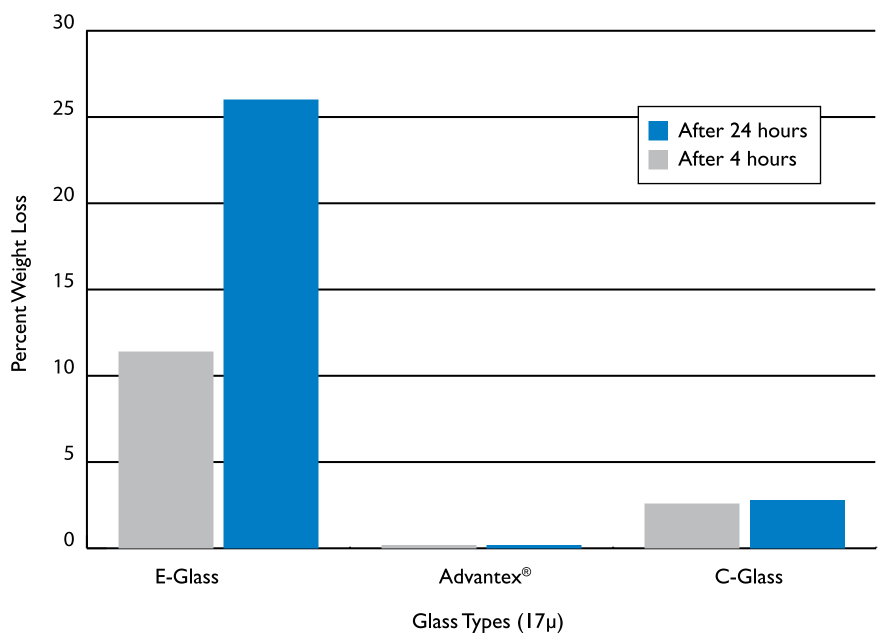


NOTES:

AQUA REGIA

Bare Glass Weight Loss Testing: Aqua Regia is a combination of hydrochloric and nitric acids and is a powerful acid as can be seen by the rapid rate at which it corrodes certain glass types. After examination, we concluded that Advantex® glass had the best performance overall and would be the best choice for the entire corrosion barrier (as veil and mat) as well as the structural portion of an FRP part to ensure the highest performance. E-glass is not recommended due to the high percentage of weight loss. C-glass veil, which normally does well in mineral acids, does not appear to be the best choice.

5% Aqua Regia @ 30°C



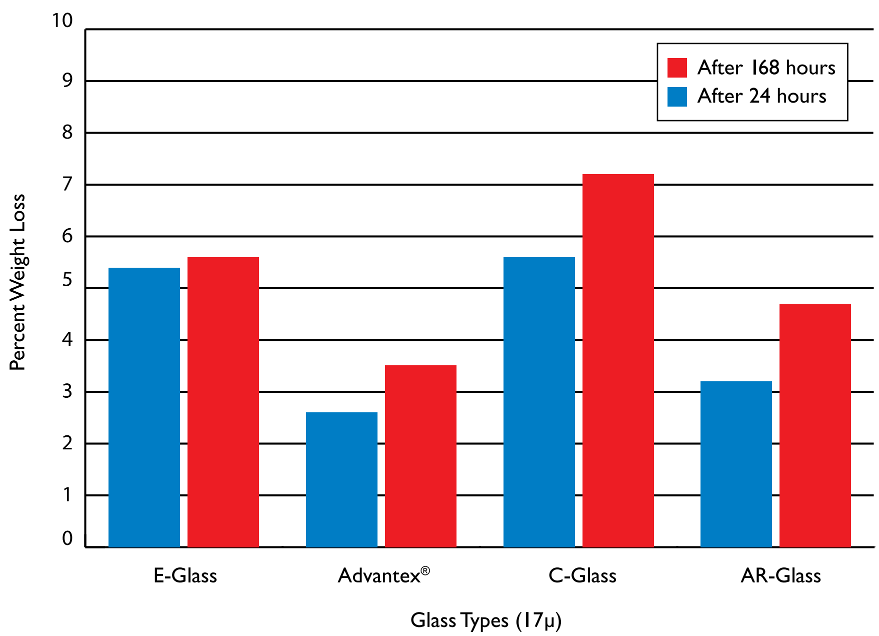
NOTES:

CITRIC ACID

Glass Fiber Chemical Resistance

Bare Glass Weight Loss Testing: Looking at the test results, Advantex® glass is the best performing fiber type and should provide the highest performance for the entire corrosion barrier (as veil and mat) and structural portion of an FRP part. Citric acid is unique among the acids shown in this study in that it will form a chelate (complex) with certain elements leached from the glass fibers. Apparently, Advantex® glass fiber does not contain as many of the elements preferred by citric acid as does E-glass or C-glass. Other studies by R.L. Jones, Curtin University of Australia, have shown a number of other organic acids such as pyruvic, oxalic, glyoxalic and malonic would corrode glass in a similar manner.

50% Citric Acid @ 96°C



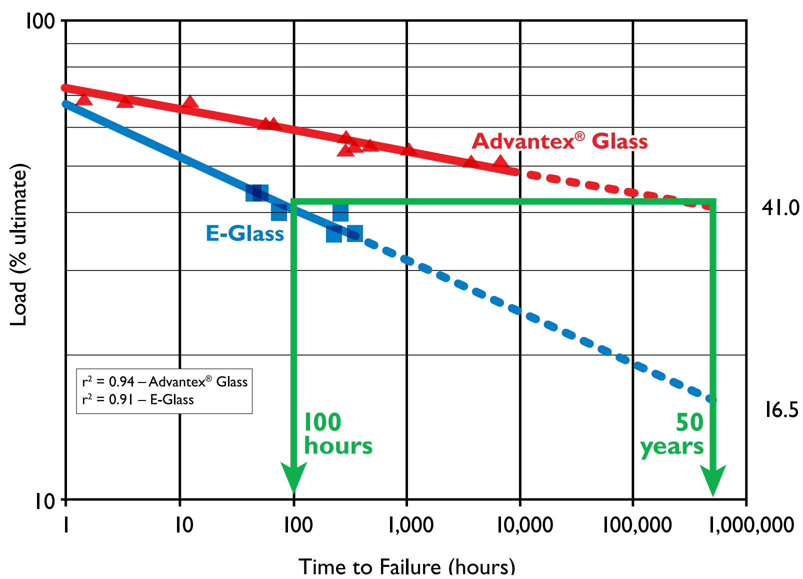
NOTES:

DEIONIZED WATER (DI)

(Also see Tap Water)

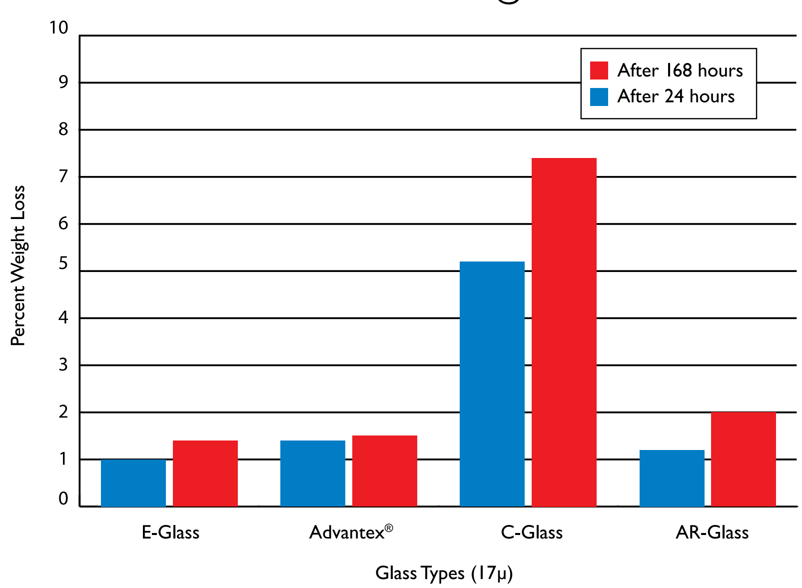
Stress-Corrosion Testing: Long-term stress-corrosion testing of composite rods shows that Advantex® glass has better durability than E-glass in de-ionized water at 25°C. Advantex® glass will retain 41.0% of its original strength after 50 years. E-glass will be able to maintain this same stress for only 100 hours. Advantex® glass is the best performer in this environment and is preferred in both the corrosion barrier (veil and mat) and structural layers of an FRP part.

Stress-Rupture Performance of FRP Rods in Deionized Water



Bare Glass Weight Loss: The difference seen in stress-corrosion testing between Advantex® glass and E-glass is not reflected in the short-term bare glass weight loss testing. Weight loss testing in DI water is not as discriminating as the more costly stress-corrosion testing. However, weight loss testing shows C-glass veil is a poor choice as the corrosion resistant barrier.

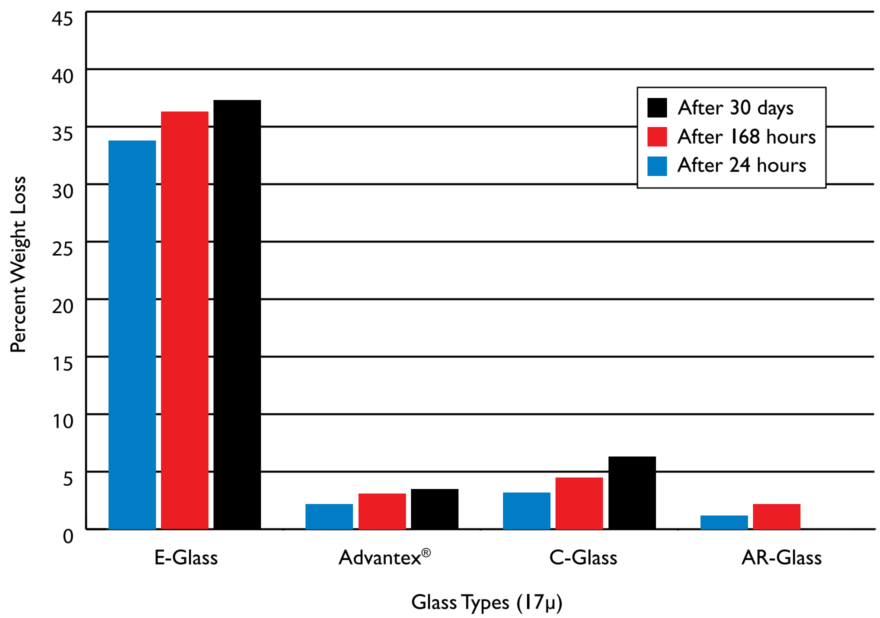
Deionized Water @ 96°C



FERRIC CHLORIDE

Bare Glass Weight Loss Testing: This test shows Advantex® glass performs better in ferric chloride and should be considered for the corrosion barrier (as veil and mat) and structural portion of an FRP part. E-glass is not a good choice for any part of a structure coming in contact with ferric chloride. AR-glass does not have the mechanical properties for the structural portion of an FRP part and is currently available for only specialty applications.

40% Ferric Chloride @ 96°C



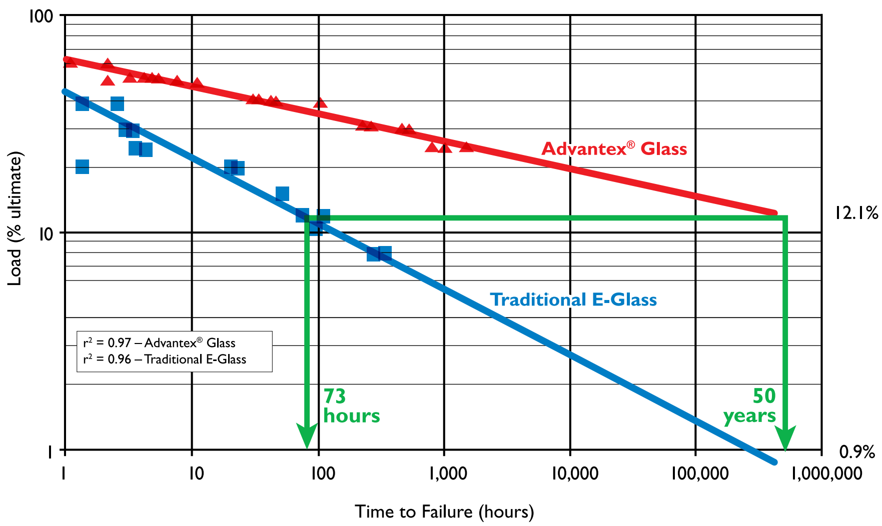
NOTES:

Glass Fiber Chemical Resistance

HYDROCHLORIC ACID

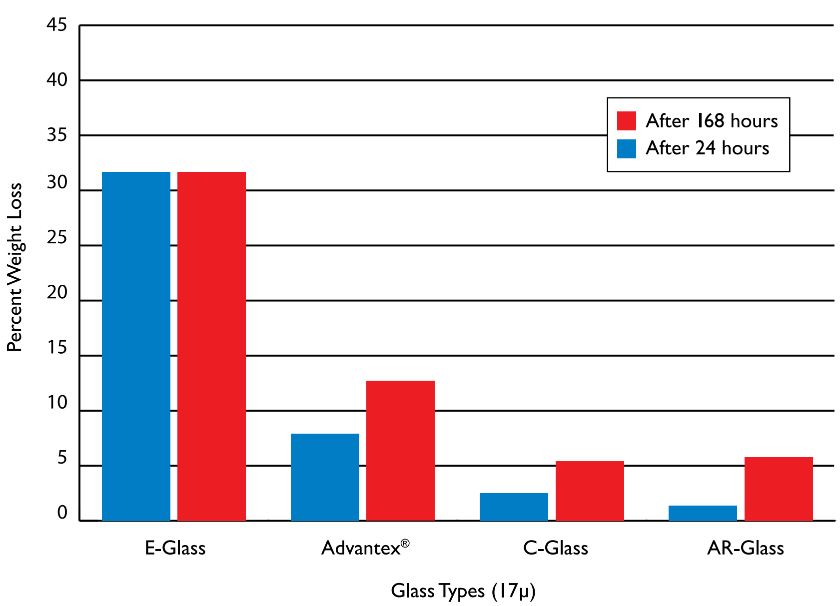
Stress-corrosion Testing: When FRP rods are exposed to the combined effects of stress and hydrochloric acid, Advantex® glass outperforms the E-glass significantly. Looking closely at the stress corrosion testing, E-glass FRP rods lose strength at a considerably faster rate than Advantex® glass FRP rods. After 50 years the Advantex® glass FRP rod would still be able to sustain 12.1% of its original load, whereas E-glass FRP rod can only sustain that load for 73 hours. The SEM photos below show why. The leaching of the E-glass fiber leads to a porous exterior and subsequent helical cracking. Advantex® glass is unaffected.

Composite Laminate Exposed 1 Normal HCL – H_2SO_4



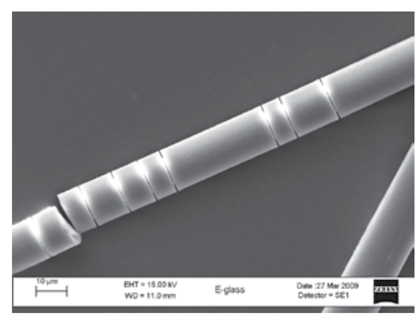
Bare Glass Weight Loss Testing: This test further supports the use of Advantex® glass for the structural portion of the FRP part. C-glass or AR-glass can be used for the corrosion barrier. E-glass is rapidly attacked by strong acids and should not be considered.

10% Hydrochloric Acid Immersion @ 96°C

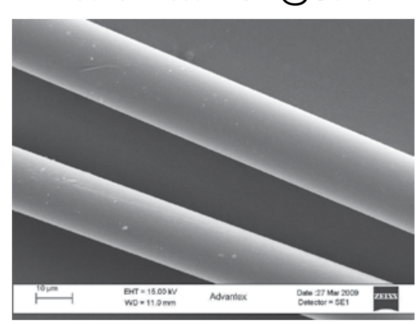


Scanning Electron Microscopy (SEM) Examination: The first picture shows classic helical cracking of E-glass fibers after exposure to 5% HCl for four hours under no stress. It is this cracking which results in premature failure of FRP parts combining stress and corrosive fluids.

E-Glass After Four Hours in 5% HCL @ 96°C



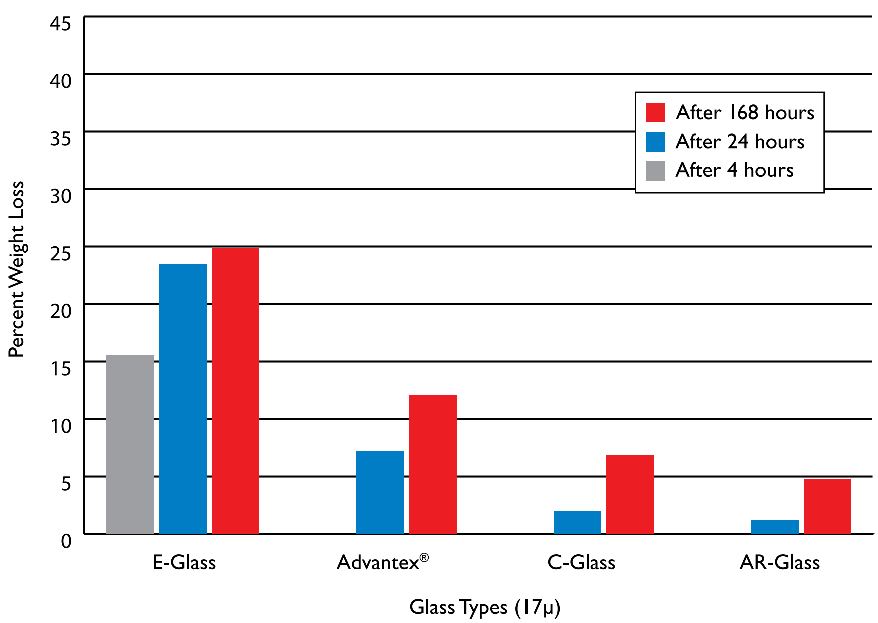
Advantex® Glass After Four Hours in 5% HCL @ 96°C



NITRIC ACID

Bare Glass Weight Loss Testing: This test shows Advantex® glass performs better than E-glass and should be considered for the structural portion of an FRP part. C-glass or AR-glass can be considered for the corrosion barrier as a veil/mat or chopped roving. This test shows E-glass is rapidly attacked by nitric acid and should not be considered.

1 Normal (4.4%) Nitric Acid Immersion @ 96°C



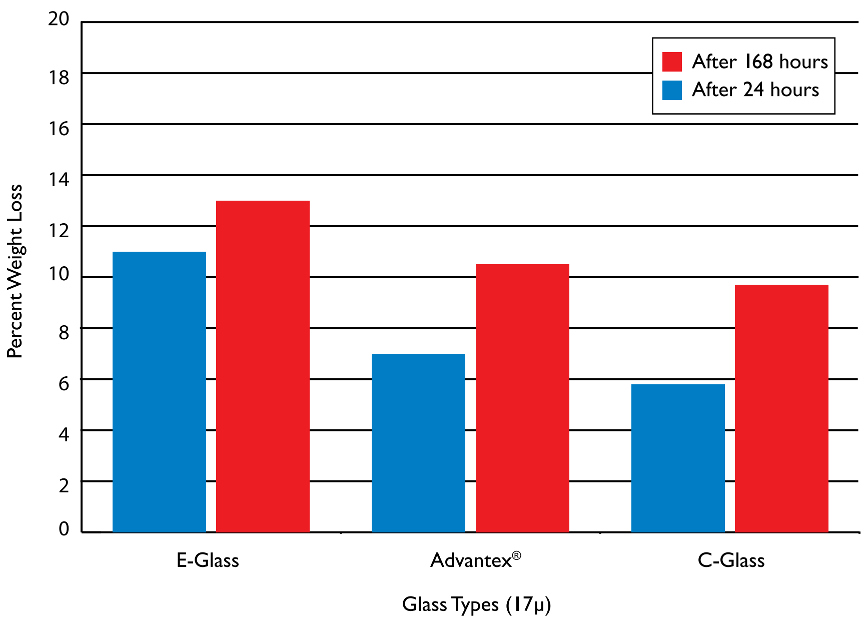
NOTES:

Glass Fiber Chemical Resistance

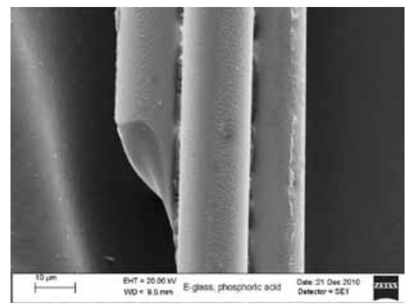
PHOSPHORIC ACID

Bare Glass Weight Loss Testing: Evidence shows Advantex® glass should be considered for the structural and mat portion of the corrosion barrier. C-glass should be considered for the inner surface veil portion of the corrosion barrier. The SEM photos show that phosphoric acid is another corrosive media that leaches elements from certain glass fiber types more so than others and re-deposits these elements (which incorporate phosphorus) onto the glass fibers. Fibers that are not leached appreciably show little re-deposition of material. The re-deposited material adds weight to the fibers making the weight loss appear less than the amount of material truly leached from the fiber. Fibers that are leached are structurally deficient.

85% Phosphoric Acid @ 96°C

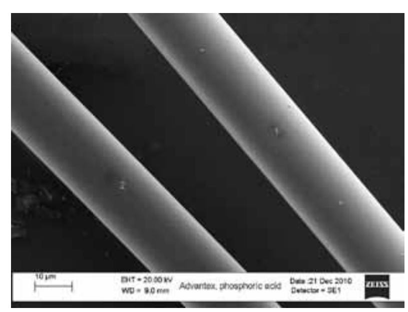


E-Glass
SEM Photo in Phosphoric Acid



E-glass shows leaching occurring with re-deposition of calcium phosphate back onto the fiber surface, likely weakening the strength of the fiber and bond to the resin.

Advantex® Glass
SEM Photo in Phosphoric Acid



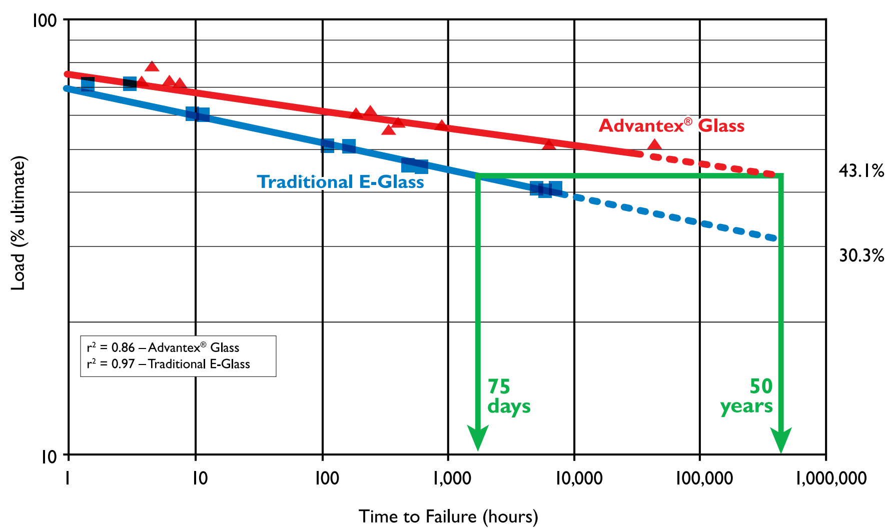
Advantex® glass shows no sign of significant leaching or weakening in phosphoric acid.

SODIUM CHLORIDE

Glass Fiber Chemical Resistance

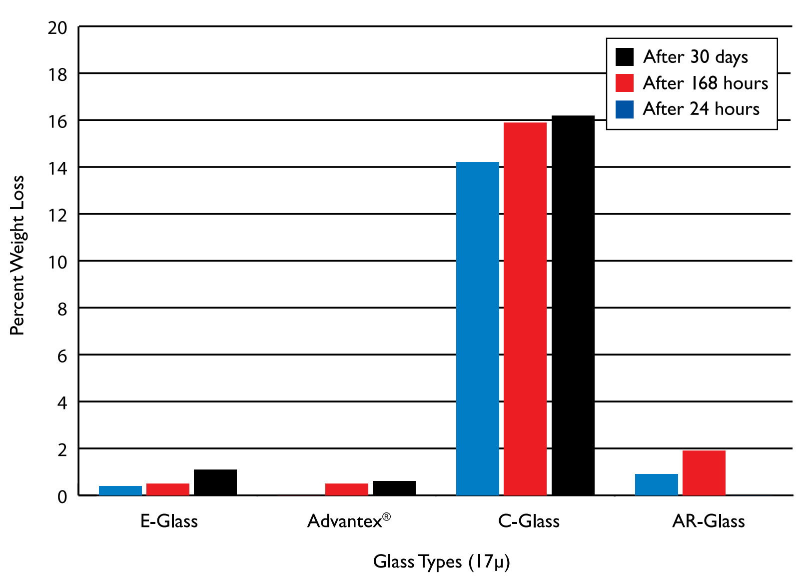
Stress-corrosion Testing: Long-term stress-corrosion testing shows Advantex® glass has an advantage over E-glass in saltwater and should be considered for the corrosion barrier (as veil and mat) and structural portion of an FRP part. The results of the test show after 50 years of immersion in saltwater the FRP rod containing Advantex® glass fiber can be expected to retain 43.1% of its load carrying capacity whereas E-glass can only carry this load for 75 days.

Stress-Rupture Performance of Composite Rods in 5% Saltwater

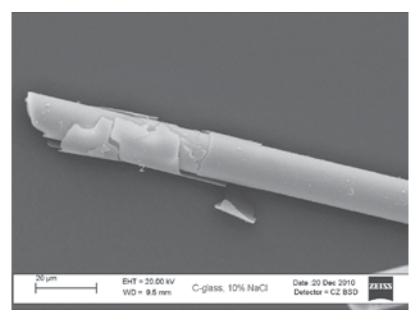


Bare Glass Weight Loss Testing: The short-term weight loss testing does not really show the important performance difference between E-glass and Advantex® glass compared to the stress-corrosion test results above. However, it clearly shows C-glass veil is a poor choice for use in saltwater. This was somewhat of a surprise but the SEM photo to the right shows this effect is real.

10% Sodium Chloride @ 96°C



SEM of C-Glass

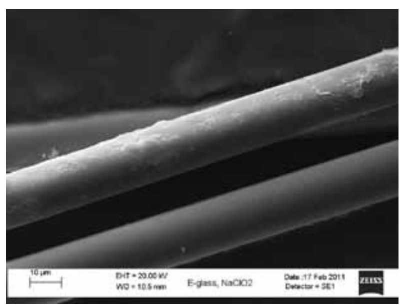


The photo is an SEM of C-glass after being exposed to sodium chloride. The speed and level of deterioration of C-glass in saltwater is significant.

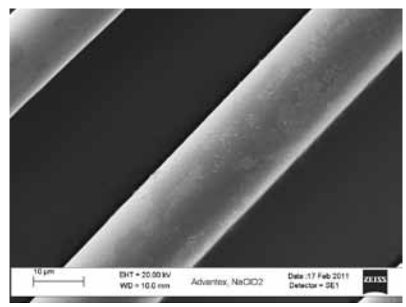
Glass Fiber Chemical Resistance

SODIUM CHLORITE

Scanning Electron Microscopy: Evidence shows the Advantex® glass is the least affected and should be considered for the corrosion barrier (as veil and mat) and structural portion of an FRP part. The weight loss testing might lead us to believe that there is only a minor difference between E-glass and Advantex® glass. However, the SEM photos show that this is another case in which leached material re-deposits onto the glass fibers and also form precipitates that are difficult to remove from the filtered glass fibers. EDX spectroscopy discovered many of these are magnesium containing precipitates. This added weight means that all fibers are leached and truly lose more weight than is reflected in the weight loss chart. The effect is less pronounced on Advantex® glass due to a lower level of leaching.



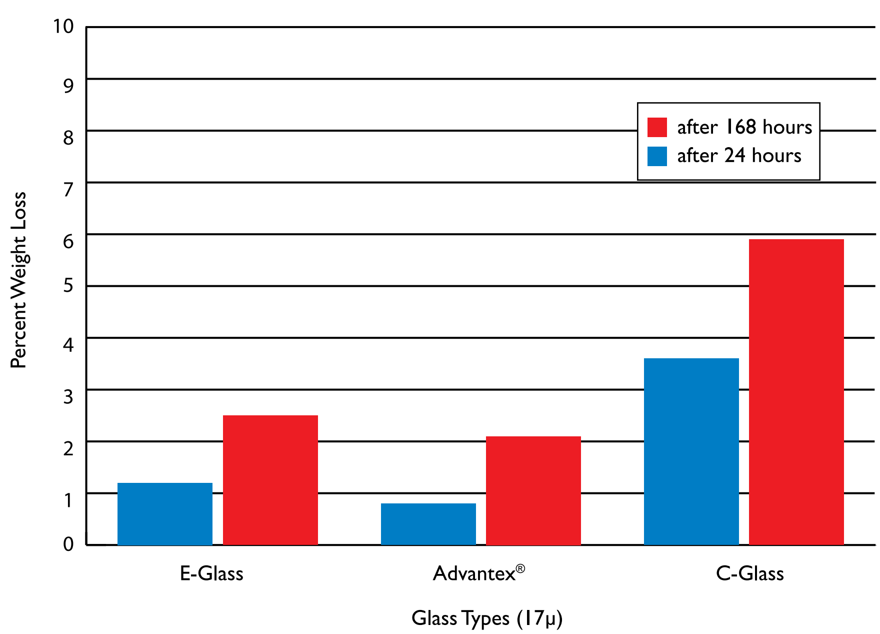
SEM of **E-glass** showing leached material re-deposited back onto the glass.



SEM of **Advantex®** glass showing minimal leaching and re-deposition.

Bare Glass Weight Loss Testing: The re-deposition effect also affects C-glass, but C-glass is also leached much more efficiently than either E-glass or Advantex® glass. C-glass would not be recommended as part of the corrosion barrier.

10% Sodium Chlorite @ 30°C – pH = 12/4

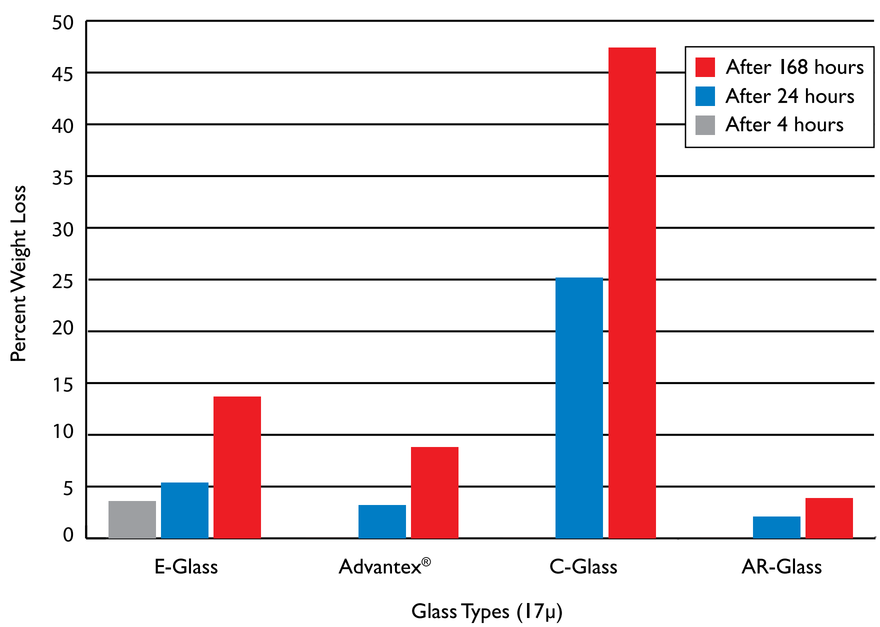


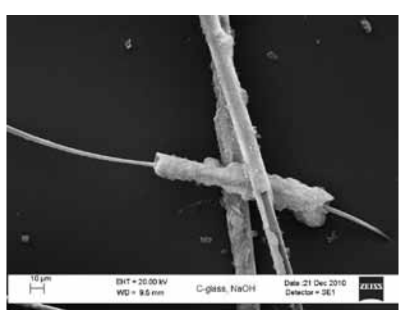
SODIUM HYDROXIDE

Glass Fiber Chemical Resistance

Bare Glass Weight Loss Testing: Corrosion in an alkaline environment proceeds via a much different mechanism than corrosion in an acid environment. Evidence shows the Advantex® glass is the least affected and should be considered for the structural portion of an FRP part. AR-glass or Advantex® glass will likely perform best for the corrosion barrier (as veil and mat). SEM photos show damage to all glass fibers types and EDX (Energy Dispersive X-ray) analysis identifies calcium, silica and sodium leached from the fiber re-deposited back on the fiber as crystalline deposits (example photo shown below). Thus, bare glass testing weight loss testing underestimates fiber damage but provides a fair evaluation of performance between the fiber types.

Sodium Hydroxide pH = 12.88 @ 96°C

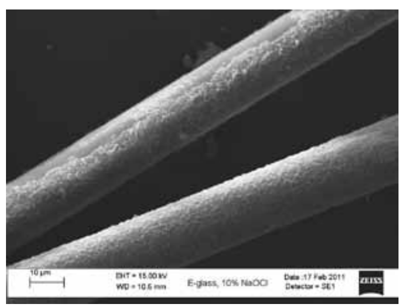




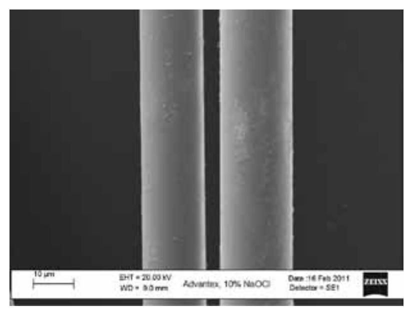
SEM of C-glass shows significant leaching and re-deposition of crystalline deposits.

SODIUM HYPOCHLORITE

Scanning Electron Microscopy: Evidence shows Advantex® glass being the least affected; it should be considered for the structural portion of an FRP part. AR-glass or Advantex® glass will likely perform best for the inner surface veil of the corrosion barrier and Advantex® glass for the mat portion of the barrier. The weight loss testing (chart below) might lead us to believe that there is little difference between E-glass and Advantex® glass. However, the Scanning Electron Microscopy pictures show that this is another case in which E-glass is leached at a greater level than Advantex® glass. The material re-deposits onto the E-glass fibers at a greater amount and also forms precipitates. Energy Dispersive X-ray (EDX) discovered much of these re-deposits are calcium containing precipitates. This added weight means that all fibers are leached and truly lose more weight than is reflected in the weight loss chart. The effect is much less pronounced on Advantex® glass.



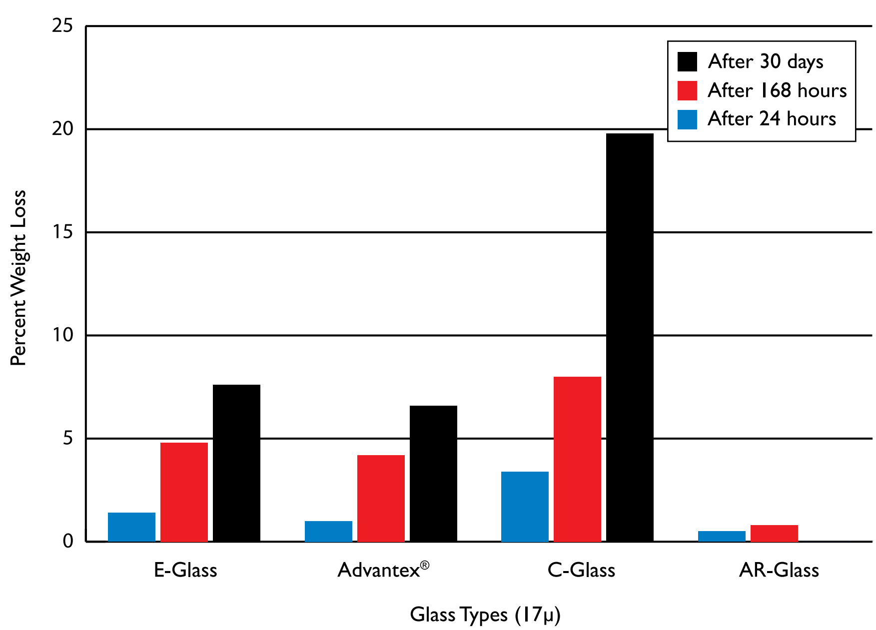
SEM of **E-glass** show leached material re-deposited back onto the glass.



SEM of **Advantex®** glass showing minimal leaching and re-deposition.

Bare Glass Weight Loss Testing: The re-deposition effect also affects C-glass, but C-glass is also leached much more efficiently than either E-glass or Advantex® glass. C-glass would not be recommended as part of the corrosion barrier.

10% Sodium Hypoclorite @ 30°C

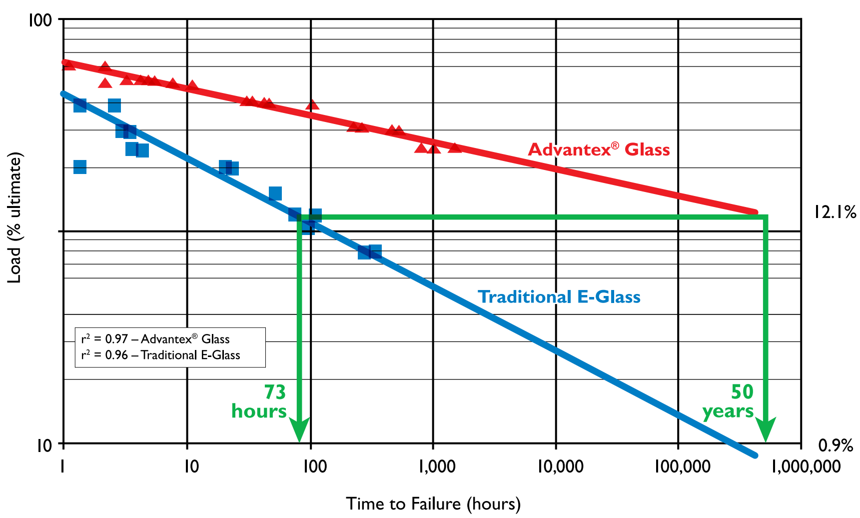


SULFURIC ACID

Glass Fiber Chemical Resistance

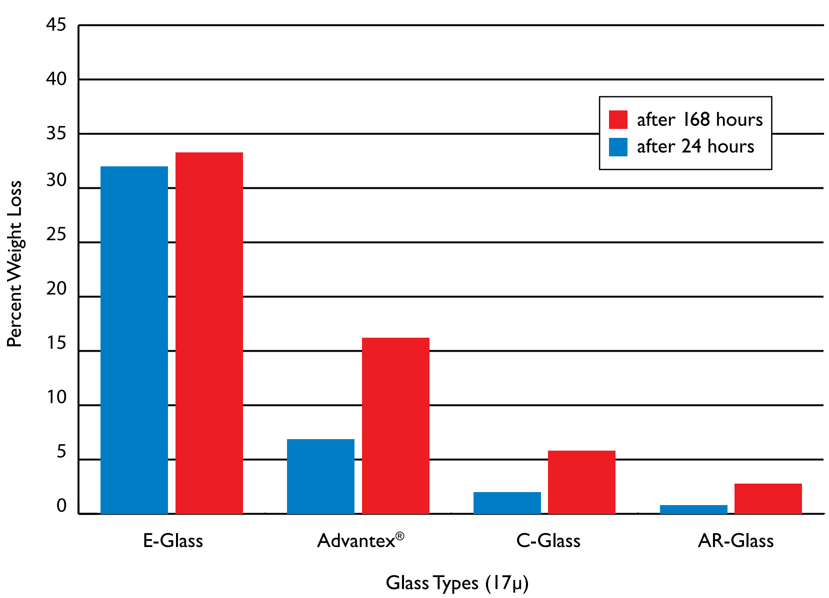
All Testing Methods: Bare glass testing shows E-glass is rapidly attacked by sulfuric acid and that Advantex® glass is the preferred reinforcement for the structural portion of an FRP part. C-glass or AR-glass is preferred for the corrosion barrier inner surface veil and Advantex® glass for the mat portion of the barrier. Stress corrosion testing confirms this large performance difference between E-glass and Advantex® glass. SEM photos of composite rods used in the stress-corrosion testing show leaching of E-glass fibers which explains the rapid loss of strength with E-glass and the higher performance of Advantex® glass.

Stress-Rupture of Composite Rods in Normal Acids (HCl-H_2SO_4)



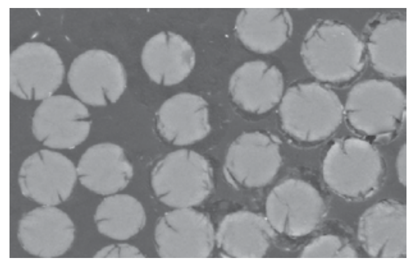
The stress-rupture test results above show Advantex® glass offers a useful stress 12 times that of a laminate made with traditional E-glass in sulfuric and hydrochloric acid applications. Another way of looking at the performance differences is by noting the traditional E-glass laminate would fail in approximately four days when stressed at the 50-year stress limit for the Advantex® glass laminate.

10% Sulfuric Acid Immersion @ 96°C



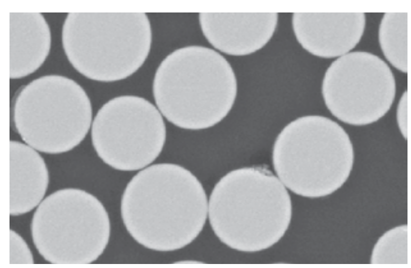
Scanning Electron Microscopy (SEM) Examination After Being Exposed to Sulfuric Acid

E-Glass FRP Rod After 3 Months



E-glass starts to break down, de-bond from the resin and weaken significantly.

Advantex® FRP Rod After 3 Months



Advantex® glass continues to perform with no leaching, maintaining its strength.

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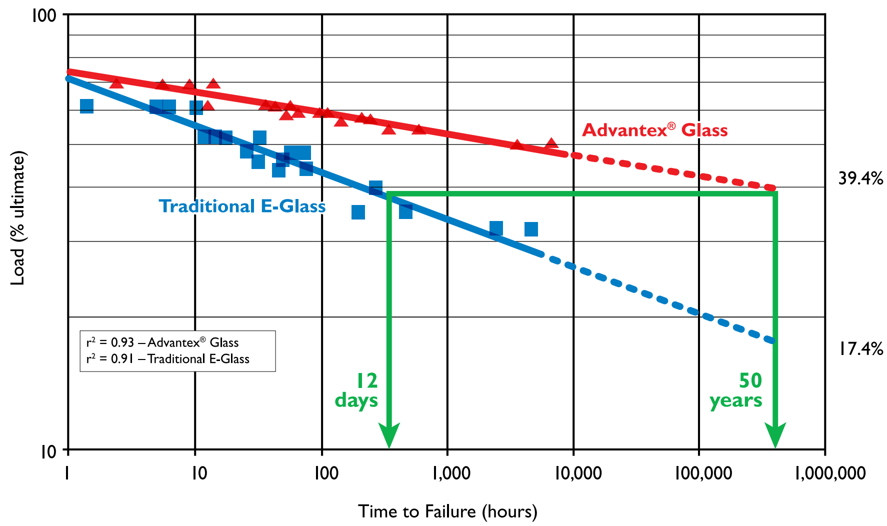
Stress-corrosion Testing: Long-term stress-corrosion testing shows Advantex® glass has an advantage over E-glass in tap water and should be considered for the structural portion of an FRP part. The results of the test show after 50 years immersion in tap water the composite rod containing Advantex® glass fiber can be expected to retain 39.4% of its load carrying capacity whereas E-glass can only carry this same load for 12 days.

Stress-Rupture Performance of Composite Rods in Tap Water



NOTES:

APPENDIX A

Description of Test Methods

1. Bare Glass Weight Loss Testing

Bare glass testing is done by first removing the protective organic sizing on the glass in such a way that the glass is not heated to its annealing point. Heating some glass types to the annealing point, particularly E-glass, can dramatically improve corrosion resistance and is not reflective of the manner in which the product is used. A specified quantity of glass fiber is weighed and placed in a corrosive media for a predetermined period of time. After this time the glass and corrosive media are filtered and reweighed. The filtrate is closely examined to ensure the contents are glass fibers, or the remains of glass fibers. If precipitate is discovered, it must be removed and only the remaining glass re-weighed. The difference between the weight before and the weight after is reported as weight loss. In this study all fibers are 17 micron fibers with the exception of C-glass which is only available in a 12 micron fiber. This roughly doubles the surface area of C-glass with respect to the other glasses and could skew the data at low levels of corrosion. Ferric chloride is the only media where this difference could be misinterpreted.

2. Scanning Electron Microscopy (SEM) Coupled with Energy Dispersive X-ray Spectrometry (EDX)

The SEM photos were taken in back-scatter mode. An interesting feature of SEM is that electrons scattered from the surface of the part being examined will reflect a greater number of electrons from more dense surfaces, such as solid glass fibers and elements with higher atomic number. Softer or porous surfaces like resin or leached glass fiber will reflect fewer electrons and voids reflect nothing. Elements of lower atomic number such as carbon and hydrogen will also reflect fewer electrons. In SEM photos, solid glass appears white or light gray, porous glass appears gray, resin appears dark gray and voids are black.

The corroded glass can be examined in either a planar or cross-sectional view. In the planar view, fibers are gently dispersed as evenly as possible on a carbon-backed adhesive, coated with either carbon or gold, then examined in the SEM photos. For a cross-sectional view, fibers are potted in an epoxy resin, cut perpendicular to the fiber lengths and polished. The polished sample is coated with either carbon or gold and then examined in the SEM. The SEM examination can include low magnifications to view the overall morphology of the fibers or magnifications of 1000X or more to identify cracks, pitting, etc. Energy dispersive x-ray spectrometry might also be used to identify chemistry differences within the fibers resulting from leaching.

3. Stress-Corrosion Tensile Testing of Composite Rods

Composite rods are prepared by pulling resin impregnated glass fiber rovings through a glass tube of known diameter. The rods are then cured according to the resin manufacturer's guidelines. The glass is then broken and the cured composite rod removed. Sample rods are taken from a single lot and tensile tested to determine the ultimate tensile strength of the lot of rods. The remaining rods are then placed in cantilevered stress-corrosion fixtures, containing the corrosive media, and loaded to a predetermined percentage of the ultimate tensile strength of the rod. Typically five different loads are selected so that failures occur at 1, 10, 100, 1,000, and 100,000 hours. The rod will fail in tension at some unknown time depending on the load, temperature and corrosive media. This time is recorded in hours and plotted. A log-log graph is prepared with the stress in MPa or "percent ultimate load" noted on the y-axis and time-to-failure in hours noted on the x-axis. A regression line is plotted to predict performance at some time in the future. A more horizontal regression line indicates little effect of the corrosive media on the composite rod. A regression line with a dramatic slope indicates that severe corrosion has occurred.

NOTES:

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