Article

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The current and future trends of composite materials: an experimental study

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Abstract

The usages of the composite materials range from simple household to light-to-heavy industrial purposes including oilfield applications. The objective of this study is to evaluate current and potential uses of composite materials for the petroleum industry. This article gathered all the available composite materials that are normally used specially in oilfield and surface pipeline applications. Out of those, four fiberglass-reinforced plastic materials (i.e., AR-glass, boron-free E-glass, C-glass, and E-glass) were selected to conduct an experiment in acidic and alkaline environments. The results show that AR-glass is corrosion resistant at high temperature and high acidic and alkaline environments. The weight loss due to corrosion is less than the other three materials. Boron-free E-glass is also better than C-glass and E-glass, especially in acidic environment. Another aspect of this research is to find out a research gateway toward the development of sustainable composites. When toxic components are used during the development of new materials, nowadays, this becomes an issue for environmental groups. Therefore, this study suggests the researchers to look for an environment-friendly, sustainable composite material that can be widely used in the petroleum industry. Finally, the trend of future research has been outlined and an indication of sustainable composite material choice has been proposed for oilfield applications.

Keywords

fiber-reinforced plastic, sustainable composite, oilfield applications, acidic and alkaline environments

Acronym

AR-glass	Alkali-resistant glass
API	American Petroleum Institute
ATP	Advanced Technology Program
CDP	Composite Drill Pipe
CFG	Cemented Fiber Glass
FRC	Fiber Reinforced Composite
FRP	Fiberglass Reinforced Plastic
GRE	Glass Reinforced Epoxy
GRP	Glass-fiber Reinforced Plastic
HDPE	High Density Polyethylene
NACE	National Association of Corrosion Engineers
NIST	National Institute of Standard and Technology
PVC	Polyvinyl Chloride
R&D	Research and development
RTP	Reinforced Thermoplastic Pipe
U.S. EPA	United States Environmental Protection Agency

Introduction

Humans have been using composite materials for thousands of years. For example, they have manufactured bricks out of mud which is thousand-year-old technology. In this modern era, we all depend on composite materials at some aspects of our lives. Fiberglass is one of the first modern composite which was developed in the late 1940s and is still the most common in our daily use. Composite is a term that has different meanings among engineers and manufacturers. In its general form, a composite material can be defined as 'a composite consists of two or more dissimilar materials which when combined are stronger than the individual

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materials.'[1] This general definition covers the various types of pipes currently being used in the oilfield and transmission of natural gas which include metal, plastic, and thermosetting resin pipes as well as various combinations of the three. A more precise definition for thermosetting composites would be 'a combination of a reinforcement fiber in a thermoset polymer resin matrix, where the reinforcement has an aspect ratio that enables the transfer of loads between fibers, and the fibers are chemically bonded to the resin matrix.'[1] It can be also defined as fiber-reinforced thermosetting or thermoplastic matrix materials.[2] Fiberglass tubular also has very specific definitions in the regulations and standards. Composite materials are normally classified as FRP or GRP, CFG, FRC, and GRE. There are varieties of composite materials which are normally graded and manufactured based on the applications. Therefore, there are no definite types or classes of composite material. However, in the oil industry, fiberglass pipes and tubulars are commonly referred to as FRP or GRE. Therefore, this study conducts an experimental investigation on FRP materials that are commercially available (i.e., AR-glass, boron-free E-glass, C-glass, and E-glass). This research also shows how these composites materials are becoming popular with time due to their significant advantages in oilfield applications that require corrosion resistance, high strength, and lightweight.

The most successful offshore applications for composites are the pipework for aqueous liquids and the paneling for both floors and walls.[3] In the downhole oilfield operations such as drilling, logging, completion, production, and workover require anti-corrosive, non-conductive, lightweight, and fatigue-resistant service tools and related piping system. To serve these objectives, composite technology has only recently become a viable means of part fabrication. Composites have been used in the automotive and aerospace industries for years and have only recently been used in the oil industry mainly in offshore applications. In addition, the uses of FRP are very crucial especially in high acidic and corrosive environment during drilling and production operations. Therefore, the increasing use of composite materials for tubular has protected the aggressive corrosion in reservoir performance and as a result enhanced the recovery of hydrocarbon. Moreover, the non-conductive and non-magnetic high-temperature polymer composites are considered to be ideal materials for construction of resistivity and induction logging tools for oil and gas exploration.[4,5] As a result, the framework of downhole tubular materials is an important part of the overall effort to produce hydrocarbons. The importance, and methods for handling and running steel and corrosion-resistant alloys, is generally understood within the industry.[6] It is always an interest to use composite materials (such as FRP and GRE tube) as a replacement for steel casings in wells. GRE tube is being used in the operation of water injection wells with corroded steel casings. This involves the inclusion of a FRP/GRE tube into the well which is completed by cement injection into space between the tube and the corroded casing in the lower part of the well. This operation allows the remainder of the GRE to be tensioned to minimize axial stress. Following this, the lower part of the casing wall may be perforated in the conventional manner and the well returned to service.

In general, almost every industry faces a shocking corrosion impact in business. NACE estimates that $300 billion per year is subtracted from US industrial operations alone.[2] A report given by Ross[2] showed that about $150 billion of these costs can be prevented by various forms of corrosion engineering and project planning. It is estimated that tubular corrosion by itself costs the oil and gas industry billions of dollars per year. The prevention of corrosion damage can be achieved by implementing alteration of environment, material selection, chemical treatment, and construction of corrosion barriers. Out of these four choices, the corrosion barrier or development of FRC material is the simplest and arguably the most effective process of these alternatives especially in downhole applications. Composite technology has advanced to the point of feasibly providing economically viable solutions to corrosion in the form of a barrier between corrosive fluids/gases and the steel in service.

The composite materials such as FRP, GRE, and other polymer–matrix composite products have been used in downhole operations since 1970s.[5] The composites used in the development of downhole tubular and other oil field applications indicated by them are a combination of a reinforcement fiber in a polymer resin matrix, where the fibers are thermally bonded to the resin matrix. The introduction of composite materials has opened the scope for operators to select lightweight corrosion-resistant alternatives instead of high-cost alloy steel in many oilfield applications. Composites are used for onshore pipelines, tanks, storage vessels, injection liners, structures, and flow lines for offshore. They are also used as composite tubing and liners for installation into tubing for downhole applications. Lined tubulars consist mainly of steel tubing with standard oilfield connections lined with composites like GRE or thermoplastic matrix materials such as HDPE and PVC.[2]

The objective of this study is to evaluate current and potential use of composite pipe in the oilfield and surface pipeline applications. Because of the similarity in applications between natural gas and some parts of the petroleum production system, applications in the petroleum industry are reviewed extensively. However, this investigation spent considerable time looking at a particular type of composite material, specifically FRC (i.e., FRP). This material often referred to as fiberglass material (other fibers besides glass are also used) which is the main focus of this study. Series of experiments were conducted to investigate the corrosion failure. Based on the experimental results, AR-glass was found to be the most effective at corrosive environment especially for downhole assembly. Finally, the trend of future research has been outlined and an indication of sustainable composite material choice has been proposed for oilfield applications.

Application of FRP materials

Oil industries use FRC materials effectively. The applications include flow lines, down-hole tubing for injection and disposal wells, sucker rods, storage tanks, process vessels, and piping for offshore firewater systems.[7,8] Composite directional drilling systems and production risers for offshore tension leg platforms are currently being developed and tested for future oilfield use.[9–12] FRP has been used extensively worldwide during the past three decades, in both onshore and offshore applications throughout the petroleum industry. Major applications include gathering and transmission line pipes for hydrocarbon and downhole tubing in onshore uses.[6,8,13] API has specifications in governing the use of low- and high-pressure fiberglass line pipes and downhole tubings.[14] FRP pipe is attractive as an alternative production tubular primarily because of its corrosion resistance, especially against oil field corrodents such as CO_2, H_2S, and production water. In offshore applications, major uses of FRP products include secondary structures such as railing, grating, walkway, cable tray, water cooling, and non-hazardous waste water lines.

Bowers and Mayfield[15] noticed that the first use of CFG tubular was in The Shell Denver Unit, Wasson San Andres Field, and Gaines and Yoakum Counties, Texas. The authors mention that they had no problems to using fiberglass tubulars in petroleum applications. Other than perforating with a hollow carrier gun and using packers without slips in the fiberglass, no special consideration is normally given the fiberglass pipe. Bowers and Mayfield[15] mentioned that prior to November 1969, the use of downhole fiberglass tubulars (fiberglass-reinforced thermal resin pipe) in Shell's Mid Mid-Continent Division was limited to a few tubing strings in shallow corrosive wells, and uncemented liners to control fill in open-hole completed injection wells. This limited application was due to very conservative burst, collapse, and tensile strength ratings by the manufacturers and a lack of knowledge of the suitability of fiberglass as cemented and perforated downhole tubulars.

Stringfellow[6] presents a basic level overview of the material properties of FRP tubulars, including a comparison with K-55 steel tubulars, with emphasis on the impact these properties have on the make-up of the API 8 Round connections. The requirements for sufficient framework of FRP tubulars are discussed along with the development of a specialized tool to use in making up FRP tubulars. He also presented a description of a power tong developed specifically for the make-up of FRP tubulars. He mentioned design parameters, used in the design of this tong, as well *P-S* laboratory and field test results.

Lou and Souder[14] summarized the initial results of a NIST/ATP of the US Department of Commerce Project, and Composite Drill Pipe. The authors mentioned that progresses have been made in three areas such as design and testing of the composite-to-metal interface at the tool joint, material and process characterization, and initial horizontal drilling trials of composite pipe segments. The significant accomplishment is the successful horizontal drilling trials of composite drill pipe segments at the Amoco Catoosa drilling research facility. The potential benefits of the composite drill pipe product in offshore oil and gas E&P operations have been discussed.

Leslie et al.[16] present the specifications for the composite drill pipe for the National Energy Technology Laboratory, US Department of Energy. The authors highlight the three limitations of conventional metal drill pipe. These are transfer of data between the bottom hole assembly and the well head is currently cumbersome, slow, and less precise than desired. To overcome those shortcomings, they have suggested cost-effective CDP which provides enabling capability in all three of these areas. A detailed analysis is outlined in their article.

Ross[2] examines the use of GRE as a barrier to downhole tubular corrosion. He pointed out that the practice of lining steel pipe with GRE composites has gained wide acceptance over the past 20 years. He explained the advantages of GRE composite materials over conventional steel. He outlined the manufacturing procedure and showed the economic viability of using the composite materials for oilfield applications. The author mentioned how corrosion damages the oilfield business and how to overcome those problems.

To overcome the limitations of metallic materials, an alternative material such as composites is the promising choice for the construction of coiled tubing. Fibrous composite materials can be tailored to exhibit unique anisotropic characteristics to optimally address burst and collapse pressures as well as tensile and compression loads. The results of an investigation to study the potential of composite materials to improve the performance of coiled tubing are presented by Sas-Jaworsky and Williams.[17] Their findings show how one can choose FRP instead of metallic materials.

Composite materials properties and composition

This investigation has focused on composite materials that are used in oilfield application and surface facilities. The earlier mentioned definition or characteristics of composites that make them ideal candidates for oilfield application include resistance to chemical and cathodic corrosion, high strength, light weight, and flexibility.[18] Generally speaking, composites have a higher strength-to-weight ratio than steel. With the ability to control the type, amount, and direction of application of the reinforcement material, composite materials become an ideal candidate for widely varying pressure applications. There are a number of different resins and fiber reinforcement materials used in composite downhole oilfield operations today. Glass fiber is the most prevalent reinforcement material, used in over 90% of all resin/filament composites manufactured today. The most prevalent resins and reinforcement material types used today are described below.[17,19]

Resin

- General purpose polyester resins – they are classified as orthophthalic polyesters having a wide range of uses in the FRP industry; they have moderate strength and corrosion resistance, they cure at room temperature, and have the lowest cost.
- Improved polyester resin is classified as isophthalic polyesters; it has good strength and corrosion resistance, also widely used in FRP corrosion applications such as room temperature cure; it is slightly more expensive than general purpose polyester resins.
- Vinyl ester resin is a chemical combination of epoxy and polyester technology, has a very good corrosion resistance, superior strength, and toughness properties and is of higher cost which is widely used as corrosion liner in FRP products bisphenol-A fumarate, chlorendic resins are a exotic system for improved corrosion resistance in harsh environments having a higher temperature capability, they are higher cost resins used widely in the paper and pulp industry.
- Phenolic resins have excellent flammability properties including flame retardance and low smoke emissivity, lower elongation, moderate strength, and higher cost. Applications include oilfield piping and fire-resistant systems structures.
- Epoxy resins – many types of epoxy resins are available. They have the best strength properties, generally heat-cure required, good chemical resistance, higher viscosity systems, and have higher material cost. They have a broad range of applications including oilfield piping and tanks.

Reinforcement material

- E-Glass – it has good strength, low modulus. It is the lowest cost fiber, available in many forms, commonly used in commercial and industrial products, mostly used in filament winding (pipe manufacture).
- S-Glass – it has better strength than E-glass and has higher modulus. It is a higher cost fiber, commonly used in aerospace and high-performance pressure vessel applications.
- Aramid – It has a good strength and higher modulus. It is a higher cost fiber having a very low density (one-half of glass fiber), excellent impact and damage tolerance properties, poor compression, and shear strength (Dupont KEVLAR TM falls in this category).
- Carbon/graphite – it has a wide strength range, highest modulus, intermediate density (two-thirds of glass fiber), poor impact or damage tolerance, best tensile strength, and stiffness properties with the highest cost of all the fibers.

Fiberglass pipe is generally made by one of two methods, filament winding or centrifugal casting. Filament winding can be done by hand or by a machine process. With the filament winding process, the inner diameter of the pipe is constant, while the outer diameter varies with the amount of resin and reinforcement material wound on the mandrel. Centrifugal casting is a pipe manufacturing process that applies resin and reinforcement material to the inside of a mold that is rotated and usually heated. During this process, the resin is polymerized and a pipe is formed. Using the centrifugal casting method, the inner diameter of the pipe can vary with the amount of resin and reinforcement material used, while the outer diameter is constant. Even as this method produces a high-quality pipe, it is labor intensive and not cost competitive. High-strength structural composite materials generally consist of a thermosetting plastic resin reinforced with continuous strands of fiber.[17] Fiberglass has been used as a structural reinforcement for years in the oilfield. Graphite fiber, which is used extensively in the aerospace industry, is becoming more widely accepted in many commercial and oilfield applications. Polyester, vinyl ester, and epoxy-thermosetting resins are used in oilfield, automotive, aerospace, and commercial applications. Many high-strength composite products are fabricated using the filament winding process. Filament winding provides accurate fiber placement, good process control, and high production rates at a relatively low cost.

Fiberglass is a composite material consisting of a thermosetting resin matrix reinforced by continuous filaments (fibers) of glass. Thermoset coil tube consists of a thermoplastic liner, over-wound with an epoxy-based structural thermosetting laminate.[3] The reinforcement is typically E-glass, but carbon may also be employed, according to the application and economic factors. The liner material may also be tailored to the application, but would normally be polyethylene, cross-linked polyethylene, nylon 11, or PVDF. There are four commonly used matrix materials which provide the chemical and temperature resistance as well as compressive and shear strengths of the composite. However, the basic components of a RTP are shown in Figure 1.

Table 1 shows the material compositions that are used in manufacturing of CDP.[16] CDP-load capability requirements and specifications are shown in Table 2.[16] These values were obtained through direct communications with numerous industry individuals and major corporations involved in offshore drilling operations.[16]

Stringfellow[6] provides a tabular and graphic illustrations of the typical properties of the unreinforced resin systems commonly used in the manufacture of downhole FRP tubulars. The glass fibers are combined with the resin system through a manufacturing process known as filament winding. The glass fibers provide the tensile properties and contribute to the strength-related moduli. These properties are influenced by the winding angle.[6] The properties for FRP downhole tubulars such as visco-elasticity, elongation, tubular sizes, weight/flexibility, and strength are normally considered. FRP materials are visco-elastic in nature. It indicates that the string will lengthen with time. FRP tubulars characteristically exhibit low elongation (maximum 3%) comparing with API Grade K-55 steel. Most of the FRP downhole tubulars are produced to inner diameter controls and have outer diameters that increase with increasing pressure rating. The FRP downhole tubular product has a high strength-to-weight to ratio, a significantly lower weight per joint, and modulus of elasticity in tension than metallic tubulars. Although FRP tubulars have a high strength-to-weight ratio, the absolute strength is lower.[6]

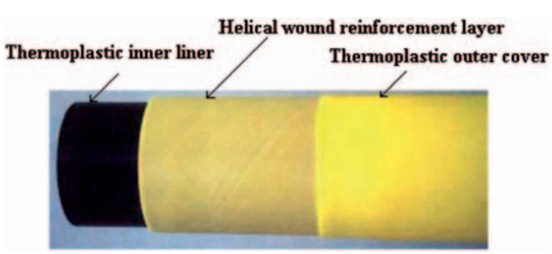

Figure 1. RTP components (redrawn from Gibson[3]).

Experimental analysis

Considering all the potential aspects, benefits, and current trend of the petroleum industry's demand, four types of FRP materials, namely, AR-glass, C-glass, E-glass, and boron-free E-glass have been selected to conduct experiment. These four FRP materials do not have styrene. Table 3 shows the chemical compositions of the FRP composite materials. Experiments were conducted to investigate the resistance to corrosion, i.e., the resistance to chemical corrosion causing weight loss of the glass fibers. Direct roving filaments were used. FRP was exposed to hydrochloric acid (i.e., HCl) and caustic soda (NaOH) solution, respectively, at different concentrations (3–10 M) and at different temperatures (25–60°C). The weight loss was calculated by measuring the weight before and after exposure. In case of alkali exposure, insoluble hydroxides were formed during exposure on the surface of the fibers. These were removed by an acid-wash procedure to obtain a proper measure of the weight loss due to alkali attack. The weight loss values obtained were corrected for the weight loss caused by the dissolution of the water-soluble part of the sizing. Moreover, it was corrected and normalized to the same specific

Table 1. CDP material specifications

Materials	Composition	
Fibers	Carbon	Commercial grade; tow size, 48–50 K; grade, 525 Ksi fiber strength, and 33–34 Msi fiber modulus
	Fiberglass	E-glass commercial grade; tow size, 450 Denier Grade: 225 Ksi fiber strength; and 10 Msi fiber modulus
Resin	350°F High-performance resin	
Adhesive	Low viscosity, high strength, and 350°F service temperature	

Table 2. CDP performance requirement specifications

Test	Results
Tension	Combined case load, Nominal operation: 20,000 TVD + 133,000 lb pull-up load + 30,000 ft-lb torsion + 7500 psi internal pressure
Compression	Combined case load, Nominal operation: 30,000 lb load + 30,000 ft-lb torsion + 7500 psi internal pressure
Torsion	Maximum make-up torque 45,000 ft-lb + 25% for shock-loading and hard-to-break connections
Tension + Bending	Combined case load, Nominal operation: 100,000 lb drag load + 30,000 ft-lb torsion + 7500 psi internal pressure + 10 degrees of bending/100 ft
External pressure	12,000 psi
Temperature	350°F nominal use
Fatigue	2,000,000 cycles (load and frequency TBD)

Table 3. Chemical composition of the different FRP materials

FRP types	Al_2O_3 (wt%)	B_2O (wt%)	CaO (wt%)	F (wt%)	Fe_2O_3 (wt%)	K_2O (wt%)	MgO (wt%)	Na_2O (wt%)	SiO_2 (wt%)	TiO_2 (wt%)	ZrO_2 (wt%)	Total (wt%)
AR-glass	0.25	–	5.41	0.35	0.09	–	–	14.40	62.20	–	17.30	100.00
Boron-free E-glass	12.80	–	22.90	0.07	0.35	0.45	4.50	0.93	58.00	–	–	100.00
C-glass	5.30	6.30	6.85	0.65	0.09	1.06	3.70	14.37	61.68	–	–	100.00
E-glass	13.30	6.20	23.28	–	0.25	0.25	0.35	0.80	55.45	0.12	–	100.00

surface area of the fiber (1000 cm^2/g). The pH was controlled and kept constant within ±0.1 during the experiments.

Results

Figure 2 shows the results of the corrosion-resistance ability of FRP (AR-glass, boron-free E-glass, C-glass, and E-glass) materials in an acid environment. The graph shows the percentage of weight loss with exposure time in an environment of 3 M HCl concentration at room temperature (i.e., 25°C). A logarithmic scale is used due to the large differences in percentage of weight loss between the FRP materials. E-glass is quickly and broadly attacked by acid environment. It reaches a weight loss of up to 11.5% in 100 h and then the corrosion rate becomes slower which reaches 12.5% after 600 h. C-glass loses its materials as much as 2.1% in 100 h, which is not very fast comparing with E-glass. However, in the long-run, it continuously loses its materials and reaches 4.5% after 600 h of acid exposure time. Both E-glass and C-glass are poor in acidic environment even at room temperature. In contrary, the corrosion resistance of boron-free E-glass and AR-glass fibers is relatively better under these exposure conditions. Initially, boron-free E-glass is better than AR-glass but after 100 h, it becomes less resistant than AR-glass. Finally, AR-glass fiber shows better for long-term use in any oilfield application at an acidic environment comparing with other three FRP materials. It is important to note that according to the experimental results, the corrosion process is different for each type of glass depending on the glass composition.

Figure 3 depicts the results of the corrosion-resistance ability of FRP materials in an acid environment with high temperature. The plot illustrates the percentage of weight loss with exposure time in an environment of 3 M HCl concentration at 60°C. The figure demonstrates that the acid resistance of the fibers glass materials is strongly dependent on the temperature. All FRP materials show a higher rate and higher levels of weight loss when the temperature is increased. E-glass, C-glass, boron-free E-glass, and AR-glass reach weight losses of up to 13%, 5.1%, 7.2%, and 4.2% in 100 h. The weight losses continue to increase as much as 25%, 12% 17%, and 9.3%, respectively in 600 h. Results show that boron-free E-glass is not good at high-temperature environment comparing with C-glass and AR-glass. It loses more weight than these two fiber materials. The long-term corrosion resistance of C-glass is predicted to be as good as that of E-glass and boron-free E-glass at elevated temperature. The difference between the corrosion resistance of C-glass fiber and the AR-glass fiber becomes more pronounced at a higher temperature. The AR-glass fiber again shows the best corrosion resistance among the fibers tested at these exposure conditions.

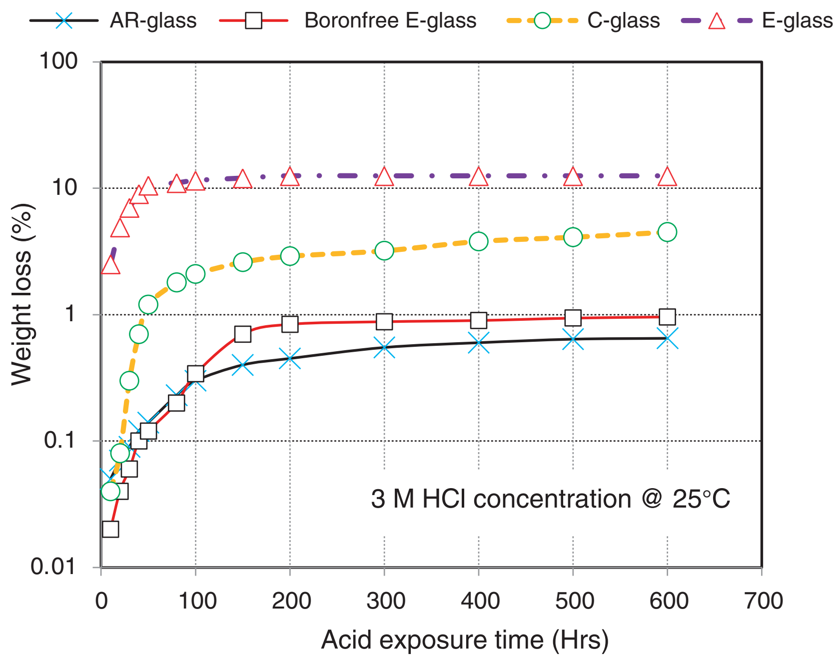

Figure 2. Percentage of weight loss of four different types of FRP when exposed to 3 M HCl at 25°C.

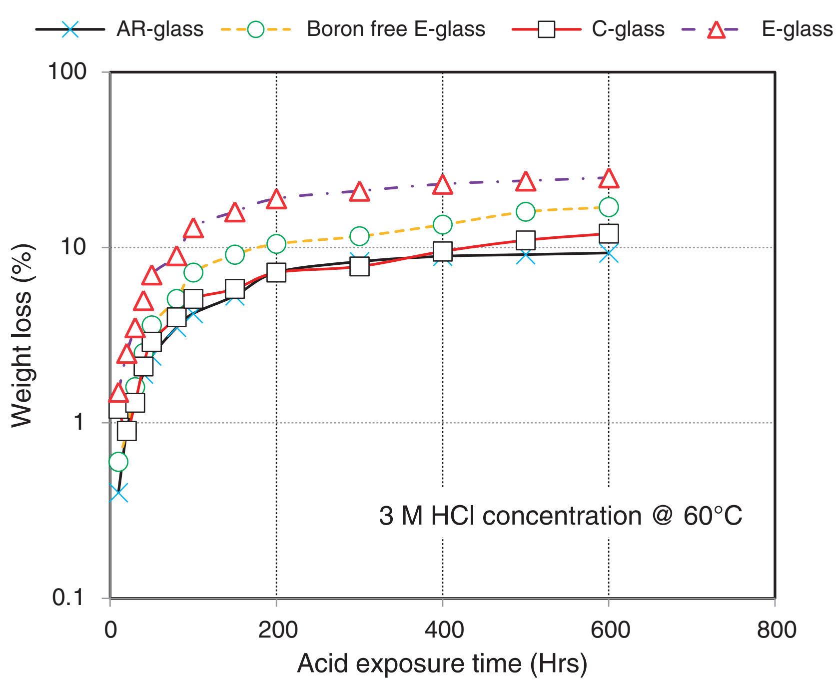

Figure 3. Percentage of weight loss of four different types of FRP when exposed to 3 M HCl at 60°C.

Figure 4 describes the same in a high-acidic concentration environment at room temperature. The fiberglass materials are tested in an environment of 10 M HCl concentration at 25°C. Weight losses of up to 38%, 16%, 13%, and 8% in 100 h for E-glass, C-glass, boron-free E-glass, and AR-glass reach, respectively. These weight losses continue to increase as much as 62%, 43%, 27%, and 18% respectively, in 600 h. The trend of the general behavior is the same as that described for 3 M HCl at 25°C (Figure 2).

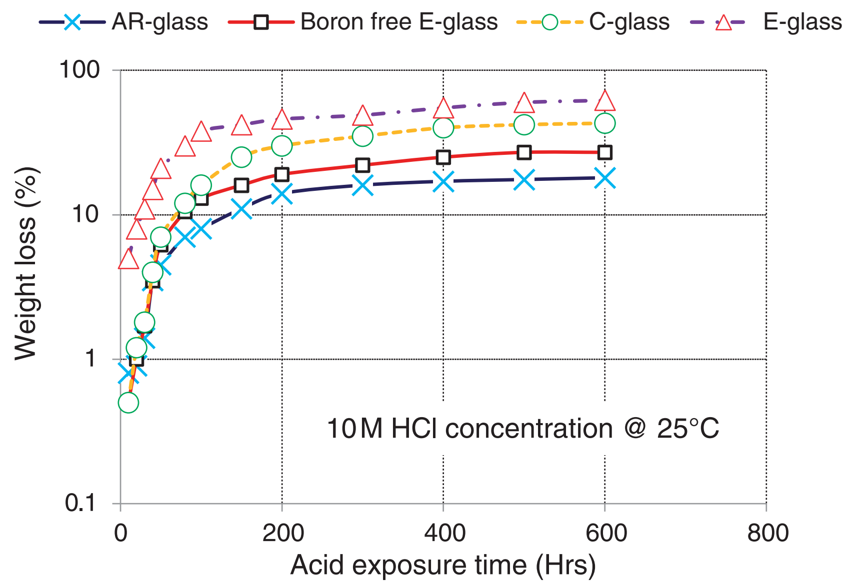

Figure 4. Percentage of weight loss of four different types of FRP when exposed to 10 M HCl at 25°C.

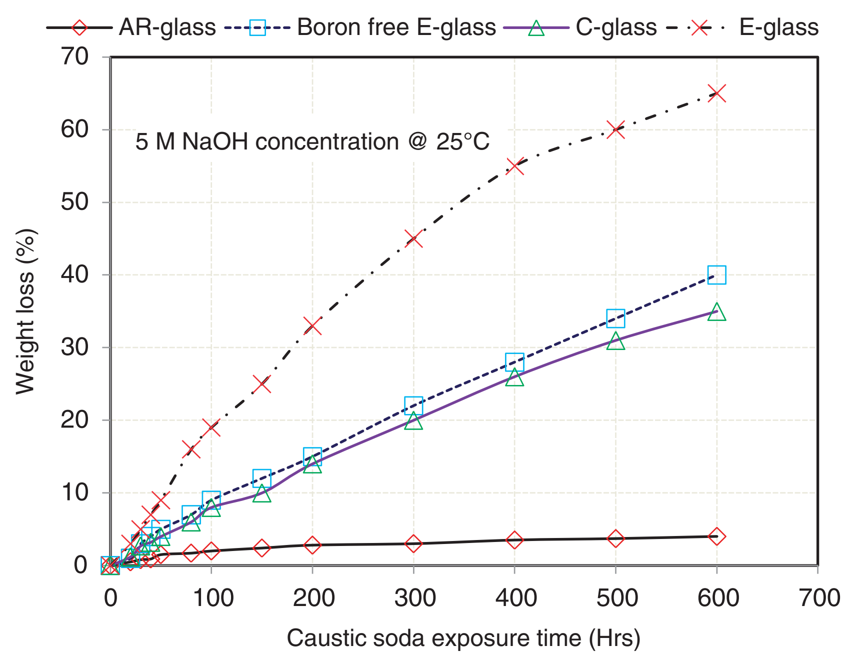

Figure 5. Percentage of weight loss of four different types of FRP when exposed to 5 M NaOH at 25°C.

However, the weight loss, at a certain time, increases with acid concentration for all fibers. The boron-free E-glass fiber and the AR-glass fiber show a similar corrosion resistance at high acid concentration comparing with other two fiberglasses. The AR-glass fiber again shows the best corrosion resistance among the fibers tested at high acid conditions.

Figure 5 depicts the weight loss in an alkaline environment where 5 M NaOH solutions are used at 25°C. There are no major differences in the trend of corrosion resistance for E-glass, C-glass, and boron-free E-glass fibers except their values. All the FRP materials lose more percentage of weight in an alkaline environment comparing with acidic environment. AR-glass has more corrosion resistance than other three fiber materials. The same behavior was observed at other concentrations. Usually, the percentage of weight loss increases with the increase of NaOH concentration.

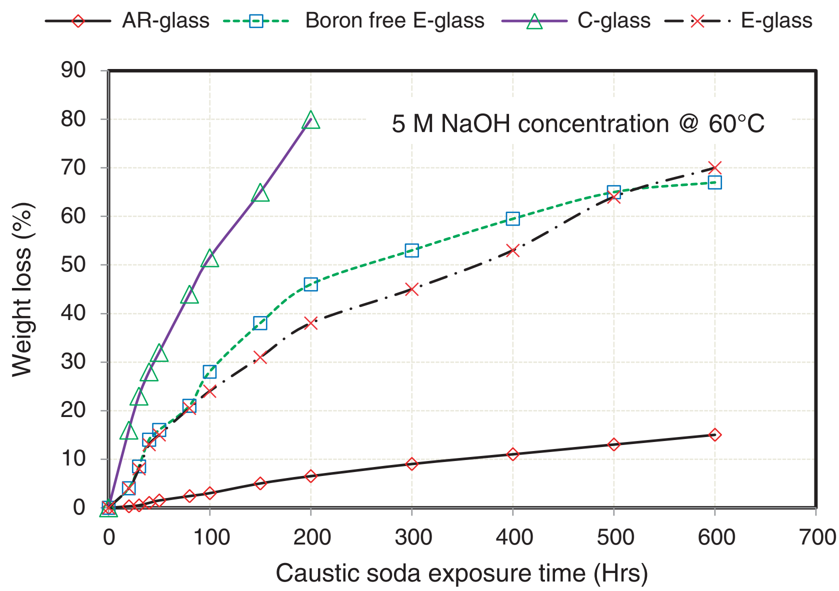

Figure 6. Percentage of weight loss of four different types of FRP when exposed to 5 M NaOH at 60°C.

Figure 6 illustrates the weight loss of the four different fiberglasses vs. the caustic soda exposure time for the same 5 M sodium hydroxide concentration at 60°C. A higher temperature increases the corrosion rate for all FRP materials. If temperature is increased from 25°C to 60°C, there is a drastic collapse for C-glass where 80% of weight loss happened in 200 h. On the other hand, boron-free E-glass and E-glass lose comparatively less weights which are 48% and 38%, respectively, in 200 h. AR-glass is corrosion resistive comparing with the other three even in alkaline with high-temperature environment. It has the height corrosion resistance to alkali.

Benefits of composite materials

There are a number of areas where composites are superior than steel. It must be noted that currently, cost of composite pipe is higher on all fronts. Composites are sold, however, on life cycle cost assessment and maintenance is the advantage. If steel is serving the need adequately, composites are usually extremely difficult to sell. Steel pipe is widely used in drilling, workover, production, gathering, transmission, and distribution of petroleum products. Comparing relative flexural strengths, composites are significantly more flexible than steel. This has several benefits, but is most relevant when combined with expansion coefficients in that fewer expansion joints are required in a composite pipe system. Composites are highly resistant to many corrosive chemicals and compounds, including H_2S. Some pipelines, including the Trans Canadian pipeline have wrapped steel pipe with composites to improve the structural properties, while at the same time, adding external corrosion resistance that the steel previously lacked. Composites are significantly lighter than steel. In fact, when strength-to-weight ratios are examined, composites can be much 'stronger' than steel. Some composites can be manufactured in continuous 'spoolable' lots that facilitate transportation and field installation. Depending on class, steel pipe ratings are generally reduced by a design factor of 0.40–0.73. Additional restrictions are used to further reduce the design factor when location or conditions warrant. Composite pipe is also re-rated in many applications, to introduce an added safety factor. Steel has better abrasion resistance. However, additives can be included in composite pipe fabrication to increase the abrasion resistance. Installation of buried composite pipe is comparable to steel, though more care needs to be taken regarding the 'trench' contents to avoid rock punctures, etc. That said, work is currently being done with resin systems that are significantly more impact resistant. Compressive edge strength of a vinyl ester-based glass composite is 24,000 psi – roughly 67% that of A36 steel.

When comparing the physical characteristics of steel, fiberglass- and plastic-based composite materials have the advantage when pressure is the critical factor. On the other hand, the advantage of CDP over its steel counterpart is that torque and tension loads at the well head can be reduced because of its lightweight, thus extending its reach in horizontal drilling.[14] The most important advantages of composite over the conventional steel are light weight, corrosion and fatigue resistance, high stiffness and strength, and design flexibility.[18] Composite material properties can be converted into important financial and performance benefits during offshore operations. Studies have shown that the use of composite products can reduce offshore capital requirements, decrease maintenance costs, and enable operations that otherwise are not feasible both technically and financially.[14] Drilling operations constitute approximately 25–40% of the total project cost; so, extended reach drilling capability is very important in offshore operations. Offshore oil and gas reservoirs are often accessed through horizontal drilling.

There are other advanced composites that are currently being used in oil field production applications. These spoolable composites are manufactured in sizes ranging from 1 to 4.5 in. and continuous lengths up to 35,000 ft. This type of pipe has a thermoplastic liner surrounded by a hybrid laminate made of carbon, glass, or other fibers in an epoxy resin base. All the strength in this pipe comes from the outer laminate layer. This allows for the use of different materials for the thermoplastic liner. CFG liners are set to control fill and provide injection profile control in open-hole completed water injection wells. Fiberglass tubulars are selected for injection well applications as the most economical alternative to steel pipe for protection from corrosive injection water.[15] Injection equipment consisting of internally plastic-coated steel tubing with packers to isolate the cross over between the steel and fiberglass casing, provide a protected system to the corrosive injection water. Fiberglass casing are normally chosen to permit periodic electrical logging to monitor flood front advance too. Fiberglass tubular can be run and cemented as liners and casing with conventional setting and cementing techniques. The fiberglass pipe will not be damaged by drilling out cement with rock bits, perforating with hollow carrier jet guns, or by most stimulation fluids. Fiberglass pipe provides an inert, corrosion-resistant system for protection of the injection interval in water flood injection wells.

Currently, the conventional heavy steel drill pipe is used, which limits the reach of the horizontal well bores roughly 7.6 km (25,000 ft). If a lightweight CDP could be developed, the frictional drag in the horizontal portion of the drill string would be reduced such that reach could be extended by 400 m to over 10 km (35,000 ft). Thus, additional wells could be accessed from a reduced number of platforms or from platforms of smaller size. Lightweight CDP would significantly reduce the required hook load and possibly the size of derrick, motor, and substructure. Thus, substantial savings could be realized in drilling operations. The flexibility of a CDP also allows the turning radius of the well to be reduced. The design advantage of composite material leads to an enhancement of drilling capability for certain formations.

As discussed in the results, AR-glass fiber shows better for long-term use in any oilfield application at an acidic and/or alkaline environment comparing with other three FRP materials. A brief discussion on the benefits of composite materials is also outlined in earlier section. Based on the above discussions, it appears that the newly developed composite material gives better quality comparing with other pipes in terms of corrosion resistant in an acidic and/or alkaline environment. The drilling operations and the production environment are totally different on different situations where geological structure, formation type, mineralogy, sedimentation, and reservoir conditions play major roles. In such situation, the conventional pipes are not suitable particularly at H_2S, NaOH and/or any other acidic/alkaline environment. If the proposed developed material is used, the quality of pipes will be improved. Therefore, usages of AR-glass are superior to any other conventional pipes used in petroleum operations.

Environmental considerations

Increased production and use of composites in oilfield applications bring up unique environmental issues that do not occur with steel production. Environmental regulatory agencies are most concerned with the use of styrene in composite manufacturing. Many different chemicals are used as monomers in composite production, but styrene is used most extensively where the environmental disaster fear appears. However, styrene is a clear liquid with a distinctive odor. Styrene is widely used because it can be combined with a variety of polymers to form resins, its physical properties when used with other polymers are well known and predictable, and it imparts important physical properties to the final product, and it is readily available and relatively inexpensive. The US EPA and other US and foreign government institutions have extensively studied styrene and its effects on humans and the environment. Some of these agencies have already reported that styrene 'does not constitute a danger to human life and health' and 'does not constitute a danger to the environment on which human life depends.'[20] However, environmental issues will become a major concern for composite manufacturers and users in the near future. In such situation, natural/biofiber composites (Bio-Composites) can be appeared as a viable alternative to glass FRCs especially in automotive and building products as well as oilfield applications.[21] Therefore, we believe that it is the right time to introduce sustainable composite materials in oilfield application. Recent research shows that it is more environment friendly and eco-efficient than the presently available composites.[21,22]

Direction of future research

An uncertain increased use of composite materials in the oil industry is the lack of simple design, and analysis tools available to evaluate the predicted performance of new composite products. Design engineers are familiar with the formulas used to develop preliminary designs for metallic parts based on internal pressure, bending, torsion, and axial load requirements. Similar design tools have not been readily available to help these engineers evaluate the feasibility of structural designs using FRC materials. The design approach presented can be used for preliminary design and analysis of composite tubular structures subjected to internal pressure, axial loads, and bending loads. Specific applications include process vessels, piping, storage tanks, hollow sucker rods, offshore risers, etc. The effects of composite degradation which can be obtained from composite journals and vendor data, may be integrated into initial design calculations.

Results of this investigation indicate there are a number of barriers that need to be overcome to make large diameter composite pipe a viable alternative for tight gas reservoir and high-pressure natural gas transportation in the future. There is a need for R&D in the areas of material science of resins and fibers; combinations of composites and traditional materials; manufacture of continuous lengths of composite pipe for tubular; on site coating or overlay of steel pipe with a composite material; armoring or coating of pipe; material failure through delamination; and joint failure and automated quality control systems. The goal of any future research should not be the manufacturing of composite materials equal to steel pipe, but to make composites the surface pipe/tubular material of choice for high-pressure large diameter natural gas transmission pipelines. It is also an interesting research to develop eco-efficient, environment friendly, and sustainable composite materials for oilfield applications. So far our knowledge, presently there are very limited research going on toward the development of sustainable composite materials for especially in petroleum industry applications.

Composite pipe use has been established in flow line, gathering line, and distribution systems associated with natural gas transmission. Flow line and gathering line systems share common barriers, but they are for the most part being adequately addressed by industry. By far, the biggest technology challenge is finding stronger, less expensive, and longer lasting pipeline materials for large diameter and high-pressure/high-volume transmission fluid systems. The barriers to using composite in tubular and transmission lines are both financial, technology and perception based. Current resin/fiber-based composite pipe is far more expensive than steel in the sizes need especially for transmission lines. However, FRP are being looked at because of their superior corrosion resistance and high strength-to-weight ratio. Experimental results show that only AR-glass has the strong corrosion resistance. The other three are moderately corrosion resistant. Therefore, it is also necessary to look back FRP materials for further improvement.

All the areas listed above are potential research areas, but some such as transportation and handling would be further in the future. Research areas that could provide quick dividends include: composite materials – resins and fibers. Combinations of exotic fibers and traditional materials are useful to maximize strength and minimize cost. Compatibility of these materials with sour gases and natural gas products; joining of composite materials, composite-to-composite, and composite-to-metal; on site manufacture of continuous lengths of composite pipe – equipment design, materials; and on site coating or overlay of steel pipe with a composite material prior to burial. Finally, it is very attractive to think in the line of sustainable composite material development. This will bring more appealing environment-friendly composite material for oilfield applications.

Conclusions

A detailed chemical composition analysis and properties of composite materials are outlined here. The experimental results show that AR-glass is more corrosion resistant in acidic environment comparing with boron-free E-glass, C-glass, and E-glass. It is also resistant at high temperature. Among the other three composite materials, the boron-free E-glass is more suitable than the C-glass and the E-glass. The environmental impact and future research trend of the existing composite material use for oilfield applications are presented as guideline. The researchers should now think how to develop an environment-friendly, sustainable composite material. The indication of sustainable composite material research is also an important issue for future research area.

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