ISIS Educational Module 8:

Durability of FRP Composites for Construction

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Objectives of This Module

The objective of this module is to provide engineering students with an overall awareness and understanding of the various environmental factors that are currently considered significant with respect to the durability of fibre reinforced polymer (FRP) materials in civil engineering applications. This is one of a series of modules on innovative FRP and structural health monitoring (SHM) technologies available from ISIS Canada. Further information on the use of FRPs and SHM systems in a variety of innovative applications can be obtained from ISIS Canada at www.isiscanada.com.

A primary motivation for using FRPs in civil engineering applications is that FRP materials are non-corrosive and thus they will not degrade due to electrochemical effects. Corrosion (rusting) of both conventional and epoxy-coated reinforcing steel in existing reinforced concrete structures has led to widespread deterioration of infrastructure systems, and this has made FRPs attractive materials in a number of concrete reinforcing, repair, and strengthening applications. However, FRPs, like all engineering materials, are potentially susceptible to a variety of environmental factors that may influence their long-term durability. It is thus important, when contemplating the use of FRP materials in a specific application, that allowance be made for potentially harmful environments and conditions. It is shown in the following sections that modern FRP materials are extremely durable and that they have tremendous promise in infrastructure applications.

The primary objectives of this module can be summarized as follows:

1. to provide engineering students with a general understanding and awareness of potentially important durability considerations for FRPs when used in civil engineering applications;
2. to facilitate and encourage the use of innovative and durable FRP materials and systems in the construction industry; this is accomplished by assisting engineers in making rational decisions based on up to date information on the durability of these systems; and
3. to provide guidance to students seeking additional information on this topic.

The material presented herein is not currently part of a national or international code, but is based mainly on the results of ongoing engineering practice, research and field studies conducted in Canada and around the world. As such, this module should not be used as a design or implementation document, and it is intended for educational use only. Future engineers who wish to apply FRP materials in a specific application should consult more complete documents (refer to Section 13 of this module).

Additional ISIS Educational Modules

Available from ISIS Canada (www.isiscanada.com)

Module 1 – Mechanics Examples Incorporating FRP Materials

Nineteen worked mechanics of materials problems are presented which incorporate FRP materials. These examples could be used in lectures to demonstrate various mechanics concepts, or could be assigned for assignment or exam problems. This module seeks to expose first and second year undergraduates to FRP materials at the introductory level. Mechanics topics covered at the elementary level include: equilibrium, stress, strain and deformation, elasticity, plasticity, determinacy, thermal stress and strain, flexure and shear in beams, torsion, composite beams, and deflections.

Module 2 – Introduction to FRP Composites for Construction

FRP materials are discussed in detail at the introductory level. This module seeks to expose undergraduate students to FRP materials such that they have a basic understanding of the components, manufacture, properties, mechanics, durability, and application of FRP materials in civil infrastructure applications. A suggested laboratory is included which outlines an experimental procedure for comparing the stress-strain responses of steel versus FRPs in tension, and a sample assignment is provided.

Module 3 – Introduction to FRP-Reinforced Concrete

The use of FRP bars, rods, and tendons as internal tensile reinforcement for new concrete structures is presented and discussed in detail. Included are discussions of FRP materials relevant to these applications, flexural design guidelines, serviceability criteria, deformability, bar spacing, and various additional considerations. A number of case studies are also discussed. A series of worked example problems, a suggested assignment with solutions, and a suggested laboratory incorporating FRP-reinforced concrete beams are all included.

Module 4 – Introduction to FRP-Strengthening of Concrete Structures

The use of externally-bonded FRP reinforcement for strengthening concrete structures is discussed in detail. FRP materials relevant to these applications are first presented, followed by detailed discussions of FRP-strengthening of concrete structures in flexure, shear, and axial compression. A series of worked examples are presented, case studies are outlined, and additional, more specialized, applications are introduced. A suggested assignment is provided with worked solutions, and a potential laboratory for strengthening concrete beams in flexure with externally-bonded FRP sheets is outlined.

Module 5 – Introduction to Structural Health Monitoring

The overall motivation behind, and the benefits, design, application, and use of, structural health monitoring (SHM) systems for infrastructure are presented and discussed at the introductory level. The motivation and goals of SHM are first presented and discussed, followed by descriptions of the various components, categories, and classifications of SHM systems. Typical SHM methodologies are outlined, innovative fibre optic sensor technology is briefly covered, and types of tests which can be carried out using SHM are explained. Finally, a series of SHM case studies is provided to demonstrate four field applications of SHM systems in Canada.

Module 6 – Application & Handling of FRP Reinforcements for Concrete

Important considerations in the handling and application of FRP materials for both reinforcement and strengthening of reinforced concrete structures are presented in detail. Introductory information on FRP materials, their mechanical properties, and their applications in civil engineering applications is provided. Handling and application of FRP materials as internal reinforcement for concrete structures is treated in detail, including discussions on: grades, sizes, and bar identification, handling and storage, placement and assembly, quality control (QC) and quality assurance (QA), and safety precautions. This is followed by information on handling and application of FRP repair materials for concrete structures, including: handling and storage, installation, QC, QA, safety, and maintenance and repair of FRP systems.

Module 7 – Introduction to Life Cycle Engineering & Costing for Innovative Infrastructure

Life cycle costing (LCC) is a well-recognized means of guiding design, rehabilitation and on-going management decisions involving infrastructure systems. LCC can be employed to enable and encourage the use of fibre reinforced polymers (FRPs) and fibre optic sensor (FOS) technologies across a broad range of infrastructure applications and circumstances, even where the initial costs of innovations exceed those of conventional alternatives. The objective of this module is to provide undergraduate engineering students with a general awareness of the principles of LCC, particularly as it applies to the use of fibre reinforced polymers (FRPs) and structural health monitoring (SHM) in civil engineering applications.

Section 1
Introduction and Overview

GENERAL

Modern societies rely on complex and sophisticated systems of infrastructure for economic health and prosperity. These systems are comprised of the roads, bridges, tunnels, sewers, and buildings that make up our urban landscapes. In recent years our infrastructure systems, many components of which are nearing the end of their useful service lives, have been deteriorating at an increasing and alarming rate; this threatens our current high quality of life.

In an effort to slow and prevent ongoing infrastructure deterioration, engineers are searching for new materials that can be used to prolong and extend the service lives of existing structures, while also enabling the design and construction of highly-durable new structures. Fibre reinforced polymers (FRPs), a relatively new class of non-corrosive, high-strength, and lightweight materials, have emerged as innovative yet practical materials for a number of structural engineering applications.

FRP materials have demonstrated strong promise in several applications. One of these involves the use of FRP reinforcing bars in lieu of steel reinforcing bars as internal reinforcement for concrete. The primary advantage of FRPs in this application is that they are non-corrosive, and are not susceptible to rusting in the same manner as steel. Corrosion of conventional steel reinforcement in concrete structures is a major factor contributing to infrastructure deterioration around the world. FRP materials also have additional advantages such as high strength and light weight. The use of FRP reinforcing bars for concrete has the potential to significantly improve the longevity of reinforced concrete structures.

Another promising application of FRP materials is in the strengthening and rehabilitation of existing deteriorated or under-strength reinforced concrete, timber, or steel structures. In these applications, FRP plates, strips, sheets, or in some cases bars, are bonded to the exterior of structures using high-strength adhesives. The externally-bonded FRP materials provide additional tensile or confining reinforcement for the structural members, thus increasing their strength and preventing further deterioration.

Additional information on the use of FRP materials in both of the aforementioned applications is available from various sources, many of which are listed in Section 13 of this module.

The reader is strongly encouraged to review ISIS Educational Modules 2, 3, and 4 for additional background information before continuing with the current document.

The focus of the present discussion is specifically on durability considerations for FRP materials when used as reinforcement or strengthening materials for concrete structures. The goal is to provide an awareness and understanding of the potentially significant durability issues associated with the use of these materials in typical construction projects. It is important to recognize that a number of different products, manufacturing techniques, component shapes, and end-use applications are available for FRP materials, and that this document cannot adequately cover them all. Refer to Section 13 for sources of additional information in this area.

WHAT ARE FRPs?

FRPs are a subgroup of the class of materials referred to more generally as composites. Composites are defined as materials created by the combination of two or more materials on a macroscopic scale to form a new and useful material with enhanced properties that are superior to those of the individual constituents alone. More familiar composite materials include concrete (a mixture of cement paste, sand, and gravel), and wood (a natural combination of lignin and cellulose).

When considering the durability of FRPs, it is important to remember that an FRP is typically a two-component composite material consisting of *high strength fibres* embedded in a *polymer matrix*. This is shown schematically in Figure 1-1. Both the fibres and the matrix play important roles in determining the long-term durability of FRPs.

Polymer Matrices

The polymer matrix is the binder of the FRP and plays many important roles. These include:

- **binding** the fibres together;
- **protecting** the fibres from abrasion and environmental degradation;
- **separating** and **dispersing** the fibres within the composite;
- **transferring force** between the individual fibres; and
- **providing shape** to the FRP component.

As we will see, the polymer matrix plays a critical role in determining the environmental durability of an FRP material, and drastic differences in durability of FRPs with different matrices have been observed for materials subjected to various environments.

Several different polymer matrix materials are currently used for FRP materials for concrete reinforcement or strengthening applications; however, one of two specific polymer types is typically used, depending on the intended

end-use for the FRP component. A class of polymers called vinylesters is commonly used for matrices in the fabrication of FRP reinforcing bars for concrete. This is due primarily to vinylesters' superior durability characteristics when embedded in concrete (discussed later). In external strengthening applications, a class of polymers called epoxies has emerged as the preferred choice. This is due mostly to epoxies' superior adhesion characteristics, which ensure a strong bond between the FRP component and the substrate concrete. A more detailed discussion of polymer matrix types and properties is provided in ISIS Educational Module 2.

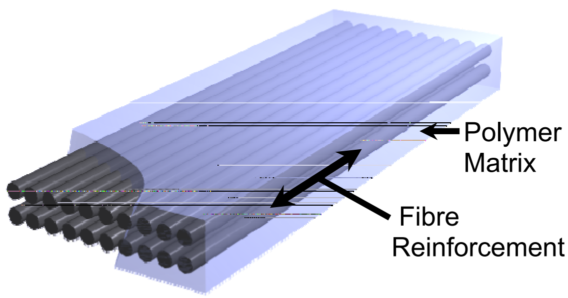

Fig. 1-1. Schematic showing combination of fibres and matrix to form an FRP composite.

Fibres

The fibres provide the strength and stiffness of an FRP, and it is thus critical that the fibres be protected against environmental degradation by the polymer matrix. The fibres that are used in most structural FRPs have extremely large length to diameter ratios (they are generally considered *continuous*) and are *oriented* in specified directions to provide strength along specific axes. FRPs are thus much stronger and stiffer in the direction(s) of the fibres and weaker in the directions perpendicular to the fibres. Fibres are selected to have:

- **high stiffness;**
- **high ultimate strength;**
- low variation of properties between individual fibres; and
- stability during handling.

In civil engineering applications, the three most commonly used fibre types are glass, carbon, and aramid. The suitability of the various fibre types for specific applications depends on several factors, including the required strength, the stiffness, durability considerations, cost constraints, and the availability of the component materials.

Glass fibres are currently the least expensive and consequently the most commonly used fibres in structural engineering applications. They are often chosen for structural applications that are non-weight-critical (glass FRPs are heavier than carbon or aramid) and that can tolerate the larger deflections resulting from a comparatively low elastic modulus. Glass fibres are commonly used in the manufacture of FRP reinforcing bars, tubes, and structural wraps.

Carbon fibres are more expensive than glass fibres. Several grades, with varying strength and elastic modulus, are available. Carbon fibres are typically much stiffer, stronger, and lighter than glass fibres, and they are thus used in weight and/or modulus-critical applications, such as prestressing tendons for concrete and structural FRP wraps for repair and strengthening of concrete structures. In addition, carbon fibres display outstanding resistance to thermal, chemical, and environmental effects.

Aramid fibres, while popular in many parts of the world, are not extensively used in infrastructure applications in North America. They have moderate cost and properties that are intermediate between glass and carbon. Additional information on fibre types and properties is presented in ISIS Educational Module 2.

FRPs

Although the strength and stiffness of an FRP material or component are governed predominantly by the fibres, the overall properties and durability depend also on the properties of the matrix, the fibre volume fraction (the volume of fibres per unit volume of matrix), the fibre cross-sectional area, the orientation of the fibres within the matrix, and the method of manufacturing. It is the interaction between the fibres and the matrix that gives FRPs their unique physical, mechanical, and durability characteristics.

Fig. 1-2. Assorted FRP products currently used for reinforcement or rehabilitation of concrete structures.

The orientation of the fibres within the matrix is a key consideration in the design and use of FRP materials. In the present discussion the focus is on unidirectional FRPs – FRPs in which all of the fibres are aligned in a single

direction. In the case of FRP materials used as internal reinforcement or strengthening materials for concrete structures, uniaxial tensile properties (strength and elastic modulus) and FRP-concrete bond characteristics are the most important parameters, since these affect the ability of the FRP materials to transfer and carry tensile loads induced in the structure.

Figure 1-2 shows various FRP products currently used for reinforcement or rehabilitation of concrete structures. The reader is encouraged to consult ISIS Educational Modules 2, 3 and 4 for additional information on FRP properties and manufacturing methods.

WHAT IS DURABILITY?

While most of us have a general sense of what the term “durability” means, is not easily defined in the context of infrastructure materials and numerous definitions have been proposed in the literature. In the current Educational Module, durability is defined on the basis of a definition offered by Karbhari et al. (2003), as the ability of an FRP element:

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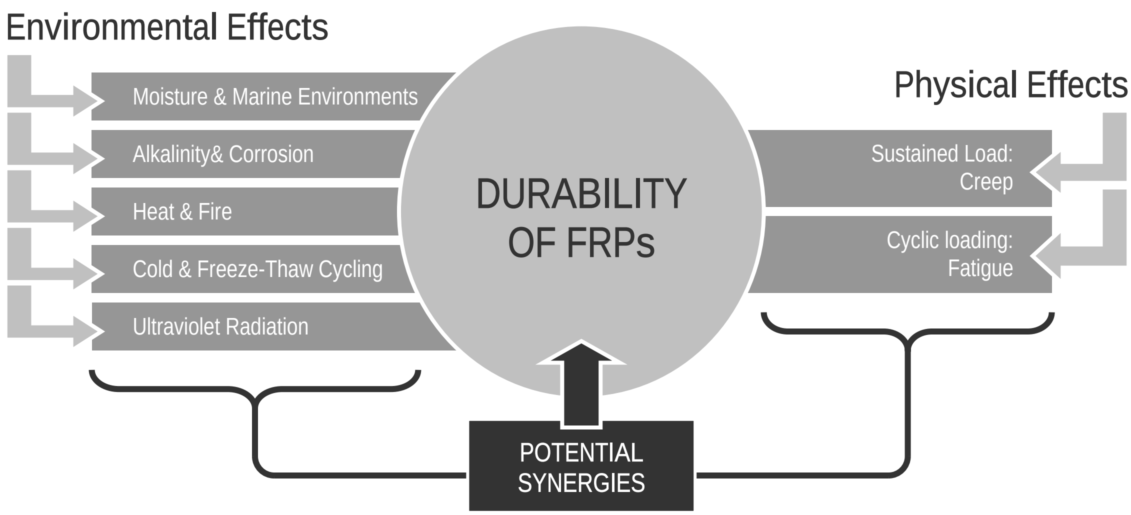

Fig. 1-3. Potentially harmful effects for FRP materials in civil engineering applications.

Section 2

Moisture & Marine Exposures

As mentioned previously, FRP materials are not susceptible to electrochemical corrosion. FRP materials are thus particularly attractive for concrete reinforcing or strengthening applications in moist or marine environments, where corrosion of conventional structural systems incorporating steel reinforcement often results in severe degradation. However, FRP materials are not immune to the potentially harmful effects of moist or marine environments.

Some FRP materials have been observed to deteriorate under prolonged exposure to moist environments, and there is evidence linking the rate of degradation to the rate of sorption of fluid into the polymer matrix. All polymers will absorb moisture, which, depending on the chemistry of the specific polymer involved, can cause a host of reversible or irreversible physical, thermal, mechanical and/or chemical changes. However, it is important to recognize that results from laboratory testing are not necessarily indicative of performance in the field, and Section 11 of this Module presents a case study which demonstrates outstanding field performance of glass FRP bars in concrete for up to eight years.

The amount of moisture absorption in a particular FRP depends on various factors, including:

- the type and concentration of liquid;
- the type of polymer resin, its chemical composition, and its degree of cure (all of which influence the amount of chemical cross-linking between individual polymer chains in the matrix);
- the fibre type;
- the fibre-resin interface characteristics (related to the chemistry of the materials used in the FRPs' fabrication);
- the manufacturing methods used;
- the ambient temperature;
- the applied stress level;
- the extent of pre-existing damage (cracking of the polymer matrix); and
- the presence (or absence) of protective coatings.

Moisture absorption in FRPs is an extremely complex topic, which remains incompletely understood and which cannot be covered in significant detail in the current Educational Module. Weitsman & Elahi (2000) provide a thorough and informative discussion in this area.

It is sufficient for the present discussion to know that moisture absorption typically results in plasticization (or softening) of the matrix caused by interruption of weak (Van der Walls) bonding between polymer chains. This can result in reductions in the polymer's strength, modulus, strain at failure, and toughness, and can subsequently cause reductions in matrix-dominated (off-axis) properties such as bond, shear, and flexural strength and stiffness. In some cases this may also affect the longitudinal tensile strength and stiffness of an FRP. Moisture-induced swelling of the polymer matrix can cause irreversible damage through matrix cracking and fibre-matrix debonding. The rate of moisture absorption typically decreases with time for most polymer matrices, as does the rate of strength and stiffness loss due to moisture absorption. These trends are shown

schematically in Figs. 2-1 and 2-2. Moisture absorption also tends to cause a mild reduction in the glass transition temperature, T_g, of polymer matrices (Chin et al., 2001). The T_g value is the temperature at which the mechanical properties of a polymer change from a rigid and brittle solid to a viscous plastic fluid, and polymer matrices are generally considered structurally ineffective at temperatures significantly greater than T_g.

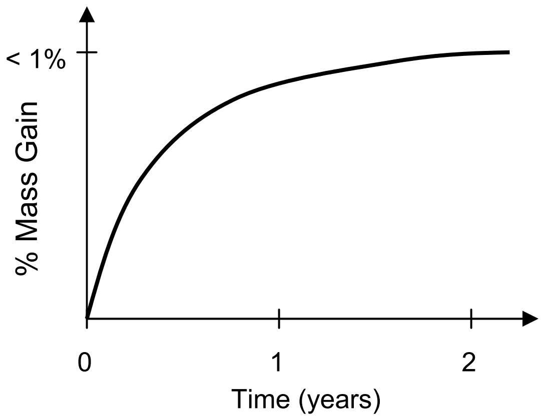

Fig. 2-1. Schematic showing typical moisture absorption trend for a polymer matrix.

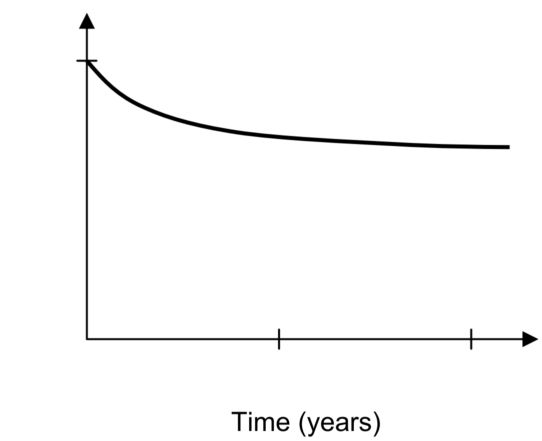

Fig. 2-2. Schematic showing typical strength loss trend for an FRP material due to moisture absorption (tensile strength in the fibre direction).

Some laboratory studies have found no tensile strength reductions due to moisture exposure while others have found tensile strength reductions of up to 57% after 10 years in deionized water at 73ºF (Karbhari, 2003), indicating that generalizations in this area are difficult to make.

Potentially important synergies are known to exist between moisture absorption effects and the effects of sustained stress and elevated temperatures, where higher levels of stress and higher temperatures appear to contribute to increased moisture absorption. These interactions remain incompletely understood, although sustained load appears to play a major role in moisture diffusion, probably due to stress-induced micro-cracking of the polymer matrix which allows moisture to penetrate further into the FRP component (Fig. 2-3). Moisture can also wick along fibres from cracks in the matrix and from cut edges of FRP components, and can subsequently damage the fibre-resin interface, contributing to reductions in structural integrity of the FRP.

Fig. 2-3. Moisture-induced microcracking of the polymer matrix in a glass FRP (Karbhari, 2003).

In the specific case of glass FRP materials, moisture that penetrates to the fibres may extract ions from the fibre and result in etching and pitting of the fibres (Benmokrane et al., 2006). This can cause deterioration of tensile strength and elastic modulus. The chemical composition of the glass fibres (standard “E-glass” versus alkali-resistant “AR-glass”) is also a potentially important factor, with AR-glass providing superior performance in most cases, particularly for applications in which FRP bars are used as internal reinforcement for concrete structures, a highly alkaline service environment. Aramid fibres are known to absorb moisture which can result in fibrillation, swelling of the fibres, and reductions in compressive, shear, and bond properties. Certain chemicals such as sodium hydroxide and hydrochloric acid can cause severe hydrolysis of aramid fibres, and these chemicals should thus be avoided. Carbon fibres do not appear to be affected by exposure to moist environments.

FRPs can be protected against moisture absorption by appropriate selection of matrix materials or by the use of protective coatings. For example, an uncracked resin-rich layer on the surface of an FRP can provide adequate long-term protection for the fibres. Vinylester resins are currently considered the best for use in preventing moisture effects in infrastructure composites, with epoxies also considered adequate. Available research also suggests that polyester resins perform poorly and should typically not be used. The importance of adequate resin curing should not be

overlooked, and additional research is required to adequately understand the influence of cure kinetics on moisture uptake by polymer matrix materials.

The effects of saline solutions have also been studied extensively to simulate exposure to both seawater and deicing salts. Testing on carbon FRP composites has indicated that decreases in strength and increases in moisture uptake are greater when the exposure solution is salt water as opposed to fresh water. In most cases, however, the effects of salt solutions have not been separated from the effects of moisture, and it has been observed that FRPs subjected to non-saline solutions show only very slightly less degradation than those in saline solutions.

Section 3
Alkalinity & Corrosion

Contrary to what most people believe, concrete is a porous material, and the pores within a solid concrete mass contain water with a very high alkalinity. The pH level inside concrete is typically more than 11, and sometimes it can be as high as 13.5. Thus, when FRP materials are used inside concrete, as in the case of internal FRP reinforcement for concrete structures, their durability in this highly alkaline environment must be evaluated. The effects of alkalinity are a concern primarily for glass FRP systems, since it has been shown in the laboratory that bare glass fibres (i.e., fibres not protected by any polymer matrix whatsoever) suffer degradation of mechanical properties under exposure to high pH solutions. For FRP materials, however, damage to glass fibres in FRPs depends also on the protection provided by the polymer matrix, the level of applied stress, and the temperature. These factors and their interrelationships are very important (and somewhat controversial), and they have thus received a significant amount of research attention. The reader should keep in mind that laboratory testing does not necessarily correlate well to in-service performance.

Glass FRPs may potentially be damaged by the alkaline environment within concrete through several interrelated mechanisms. Alkaline solutions that manage to penetrate the FRP and affect the glass fibres typically cause embrittlement of the individual fibres resulting in a reduction in tensile properties, and contribute to damage at the fibre-resin interface resulting in a reduction of both the longitudinal and transverse properties. This is likely due to a combination of mechanisms involving chemical attack by alkalis on the fibres themselves, and the subsequent growth of hydration products on the surface of the fibres (Murphy et al., 1999).

If glass FRPs are subjected to stress or elevated temperature during exposure to alkalis, deterioration of tensile properties is more severe. This can result in a phenomenon known as creep rupture (sometimes called stress rupture or stress corrosion). This issue is discussed in more detail in Section 7.

The ability of polymer matrices and protective coatings to provide protection against alkali attack is a key factor in the alkali resistance of glass FRP bars in concrete. The consensus within the research community appears to be that vinylester resins possess superior resistance to moisture and alkalinity ingress in comparison with other common resins such as epoxies or polyesters. Polyesters in particular should not be used for the fabrication of FRP reinforcing bars (Micelli and Nanni, 2004). Vinylester resins appear to be tougher and more resistant to microcracking, resulting in minimal diffusion through the matrix, and they are resistant also to various acids and other chemical solutions. Migration of highly alkaline solutions and alkali salts through the resin is always possible, however, and the potential for alkali migration is enhanced by the presence of stress, which causes the development of micro-cracks in the matrix as discussed previously, and elevated temperature, which increases sorption rates.

A large amount of test data is available from short-term tests on glass fibres in highly alkaline environments, and these data have been used to try to extrapolate the long-term performance of glass fibres. In the case of glass FRP bars in concrete, however, the performance is related not only to the chemical deterioration of the glass fibres but also to a combination of complex and incompletely understood mechanisms. There is no evidence that the available test data on glass fibres are applicable to FRP bars in concrete, and extrapolation of the results of short-term tests to field conditions is not possible without in-service performance data (refer to Section 10).

The type of glass fibre is a factor in the alkali resistance of glass FRP bars. Alkali resistant (AR-glass) fibres can significantly improve the performance of bare glass fibres in highly alkaline environments, although these are considerably more costly than standard E-glass fibres and are not required if adequate protection can be provided by the polymer matrix. Tensile strength reductions ranging from 0 to 75% of initial values have been reported for E-glass FRP bars exposed to various combinations of pH, alkalinity, temperature, and sustained stress (Murphy et al., 1999; Chen and Davalos, 2006). Tensile stiffness reductions range between 0 and 20% (ACI, 2006).

Data on the durability of aramid or carbon FRP reinforcing bars in alkaline environments is relatively scarce. With respect to aramid FRPs, tensile strength and stiffness have been reported to decrease between 10 to 50% and 0 to 20% of initial values, respectively, in elevated temperature

alkaline solutions either with or without tensile stress. In the case of carbon FRP, strength and stiffness have both been reported to decrease between 0 to 20%, although the reader should once again be cautioned against making sweeping generalizations on the basis of available data.

Clearly, the durability of FRP bars in alkaline environments, particularly in combination with elevated temperature and applied stress, remains incompletely understood. As such, conservatism is currently required when using FRP components in concrete. This is discussed more completely in Section 9, where materials reduction factors and allowable sustained service loads are suggested to account for the potentially da

properties may also be affected above T_g (Fig. 4-1). For typical FRP materials currently used in infrastructure applications, tensile strength reductions as high as 80% can be expected in the fibre direction at temperatures of only 300ºC. It is thus important that an FRP component not be exposed to temperatures close to or above T_g during the normal range of operating temperatures.

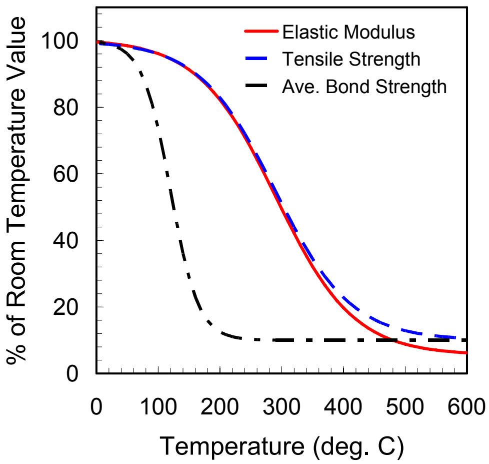

Fig. 4-1. Schematic showing typical deterioration in mechanical and bond properties for unidirectional glass FRP bars (reproduced after Bisby, 2003).

Degradation of mechanical properties is governed by the properties of the polymer matrix, since commonly used fibres are less affected by temperature. For instance, carbon fibres are essentially insensitive to temperature, showing no deterioration in strength or stiffness up to at least 1000ºC. Glass and aramid fibres experience significant deterioration of strength at high temperature, with glass fibres experiencing a 20-60% reduction in strength at 600ºC, and aramid experiencing similar reductions at 300ºC.

The temperature at which a polymer matrix will ignite, the flame spread characteristics, and the amount and toxicity of smoke produced, are all dependent on its specific formulation and chemistry. Research from the marine composites industry has indicated that the resins used in structural FRPs generate unacceptable quantities of smoke, that they have relatively poor flame spread characteristics, and that burning resins generate varying quantities of carbon monoxide, hydrogen fluoride, hydrogen chloride, hydrogen sulfide, and hydrogen cyanide, all of which are potentially harmful to humans. While there exist various resin additives that can enhance the ability of polymer materials to resist ignition, flame spread, and smoke generation, these additives tend to diminish mechanical properties, thus discouraging their use in structural applications.

The relationship between temperature and the bond between FRP materials and other materials is another potentially important factor in the high temperature performance of FRP components. Bond is typically severely affected at only slightly elevated temperatures. Research on the bond properties of FRP reinforcing bars for concrete at elevated temperature has shown dramatic decreases in bond strength, to values of about 10% of room temperature strength, at temperatures of between 100 and 200ºC (Fig. 4-1). This has been attributed to changes in the properties of the polymer matrix at the surface of the rods. Clearly, bond degradation at elevated temperatures is an important factor in the design of FRP-reinforced concrete members.

Very little information is available on the post-fire residual strength and stiffness of FRP materials for infrastructure. Research is required to determine allowable exposure temperatures and post-fire repairability of FRPs and FRP reinforced concrete members.

Thermal cycling of FRP reinforcing materials within the typical range of service temperatures does not appear to cause significant damage, other than minimal amounts of matrix micro-cracking resulting from differential thermal expansion between the fibres and the matrix, which could potentially exacerbate damage from other mechanisms such as moisture absorption.

Owing to the susceptibility of FRPs to deterioration at high temperatures, the use of FRP reinforcement is not recommended for structures in which fire resistance is essential to maintain structural integrity (ACI, 2006). Exposure to elevated temperatures for a prolonged period of time may also be a concern with respect to exacerbation of moisture absorption and alkalinity effects as discussed previously.

Section 5

Cold Temperatures & Freeze-Thaw Cycling

In cold climates such as those found in Canada, the potential for damage due to low temperatures and thermal cycling must be considered whenever FRPs are contemplated for use in outdoor applications. Freezing and freeze-thaw cycling may affect the durability performance of FRP components through changes that occur in the behaviour of the component materials at low temperatures, or due to differential thermal expansion between the polymer matrix and fibre components or between concrete and FRP materials. This could result in damage to the FRP or to the

interface between FRP components and other materials such as concrete.

While a wealth of information is available on the behaviour of aerospace FRPs at low temperature, comparatively little data are available on the cold-regions durability of FRPs used for infrastructure applications. Polymers typically have coefficients of thermal expansion that are substantially greater than commonly used fibres. Exposure to subzero temperatures can result in the development of residual stresses in an FRP component due to matrix stiffening at cold temperatures in combination with differential thermal expansion between the fibres and the polymer matrix. These stresses may contribute to matrix micro-cracking and fibre-matrix bond degradation. Micro-cracks may subsequently grow under repeated freeze-thaw cycles to form transverse matrix cracks and result in fibre/matrix debonding. This can affect FRPs' stiffness, strength, dimensional stability, fatigue resistance, moisture absorption, and resistance to alkalinity. Freeze-thaw cycling in combination with marine or deicing salts is thought to be more damaging due to the potential formation and expansion of salt crystals within the FRP (Shao and Kouadio, 2002), although this has apparently not been extensively studied for infrastructure composites.

The tensile strength of unidirectional FRP materials in the fibre direction typically decreases in the -10 to -40ºC range, whereas the transverse strength may actually increase somewhat due to matrix hardening. Increasing numbers of freeze/thaw cycles have been shown to result in increased severity and density of matrix cracks, increases in matrix brittleness, and decreases in their tensile strength. However, the effects on FRP properties appear to be minor and should not be a serious concern in most infrastructure applications.

The coefficients of thermal expansion (CTEs) of various currently available infrastructure FRPs can vary widely. The longitudinal CTE of glass FRPs is similar to that of concrete, thus reducing the likelihood of differential thermal expansion. Carbon and aramid FRPs, however, have coefficients of thermal expansion that are typically an order of magnitude different than that of concrete, and while no field evidence exists that this is problematic, the potential does exist for damaging differential thermal strains under large changes in temperature. The coefficients of thermal expansion of FRPs in the transverse (matrix-dominated) directions are typically much greater than that of concrete, leading to concerns that changes in temperature could cause splitting failures of the concrete cover when FRPs are used as internal reinforcement for concrete, or that the bond between FRPs and concrete might be damaged in externally-bonded applications. Again, damage resulting from transverse thermal expansion has apparently not been

Section 8

Cyclic Loading (Fatigue)

Virtually all structures are subjected to repeated cycles of loading and unloading called ‘fatigue’ cycles. These cyclic fatigue loads may result from moving loads such as traffic, thermal effects such as differential thermal expansion, wind-induced or mechanical vibrations, or assorted other effects, and can eventually cause failure of structural components under stress levels that are less than ultimate.

A wealth of information on the fatigue behaviour of FRP materials is available from the Aerospace literature, although the available information is not strictly applicable to FRPs used in infrastructure applications. Only very limited long term fatigue data are available for infrastructure FRPs. The available data appear to indicate that the fatigue performance of FRPs is typically as good as or better than steel.

The properties of the polymer matrix used in the fabrication of the FRP component appear to play a more significant role in the fatigue performance of FRPs than the type of fibres used, since most fibres are relatively insensitive to fatigue effects. Good fatigue performance in FRPs depends largely on the toughness of the matrix and its ability to resist cracking, both of which are also important with regard to other durability damage mechanisms discussed previously.

Carbon FRPs appear to have the best fatigue performance among the three common FRPs used in infrastructure applications. Glass FRPs have also demonstrated good fatigue performance. Aramid fibres display excellent fatigue performance, with very little fatigue-induced strength degradation.

High temperature and humidity, as well as the presence of moisture or corrosive fluids, degrade the fatigue performance of FRP materials, although again it is difficult to make generalizations, since data from individual test programs are influenced by the test methods used and the specific FRP material being studied. Other potentially important synergistic factors include alkalinity, manufacturing technique, stress ratio, stress intensity, the gripping mechanism used during testing, and the specific application.

Because carbon fibres themselves are resistant to environmental degradation due to most other effects, the fatigue life of carbon FRPs is essentially unaffected by moisture and temperature, unless the resin or fibre/resin interface is degraded by the environment. However, results from one specific study found that the fatigue strength of CFRP bars encased in concrete decreased when the environmental temperature increased from 20ºC to 40ºC (Adimi et al., 1998). It was also found that higher loading frequencies resulted in lower fatigue lives due to increased bar temperatures resulting from sliding friction.

For glass FRPs, other environmental factors appear to play important roles in determining the fatigue behaviour, although again it is difficult to clearly separate the effects of various damage mechanisms. Moisture and alkaline and acidic solutions may degrade the fatigue performance of glass FRPs due to reductions in the strength and stiffness of the glass fibres and damage to the polymer matrix and fibre matrix interface, as previously described.

Because aramid FRP bars are, in some cases, susceptible to degradation from moisture and elevated temperature, these exposures also appear degrade the long-term fatigue performance of these materials.

Insufficient information is currently available to allow the assessment of the long term fatigue performance of most specific FRP materials when subjected to various environmental conditions based on short-term laboratory testing, and additional research is clearly required in this area.

Section 9

Reduction Factors & Stress Limits

As outlined in the previous sections, numerous factors exist that can potentially affect the long term durability of FRP materials in civil engineering and construction applications. In most cases, these factors remain incompletely understood, as do the complex interactions and synergies that may exist between them. To account for degradation of mechanical and bond properties due to many of the factors discussed above (in addition to other factors not discussed here), reduction factors have been suggested in various existing design codes and recommendations. These factors are applied to the nominal stress and strain capacities of FRPs and essentially limit the useable ranges of stress and strain in engineering design. As an example, Table 9-1 provides a summary of currently suggested reduction factors for FRP reinforcing bars prescribed by existing guidelines and codes for reinforcement of concrete with FRP bars. It should be noted that these reduction factors have been developed to include both environmental and non-environmental considerations in some cases, and they should thus not be compared from document to document.

The suggested reduction factors in the above table show that carbon FRPs are generally considered most resistant to degradation, with aramid FRPs less resistant and glass FRPs least resistant.

In addition, current design documents also suggest that sustained (service) stress levels be limited to avoid creep rupture and other forms of distress. Various different stress limits have been suggested in the literature for different types of FRP reinforcing materials in different applications and under different environmental conditions; examples are presented in Table 9-2, again for FRP reinforcing bars for concrete. The variability, and sometimes disagreement, that has been observed in durability related studies is evident in the suggested stress limits, although there appears to be a consensus that carbon FRPs are least susceptible to durability effects, while glass FRPs appear to be most susceptible.

Table 9-2 clearly shows the concerns associated with creep effects and creep rupture for some FRP materials, particularly glass FRPs where the allowable sustained stress is limited quite severely.

The reader should be reminded that the reduction factors and stress limits presented in Tables 9-1 and 9-2 are based on relatively scarce data. The values presented are considered conservative and require revision as more complete information on the long-term performance of FRP materials in infrastructure applications becomes available.

Table 9-1. Summary of suggested reduction (resistance) factors for non-prestressed FRP reinforcing bars in North America

Document	Material	Exposure Condition	Reduction Factor
Canadian Highway Bridge Design Code (CSA, 2006)	AFRP	All	0.60
	CFRP	All	0.75
	GFRP	All	0.50
Design and Construction of Building components with Fibre Reinforced Polymers (CSA, 2002)	All	All	0.75
Guide for the Design and Construction of Concrete Reinforced with FRP Bars (ACI, 2006)	AFRP	Not exposed to earth and weather	0.90
		Exposed to earth and weather	0.80
	CFRP	Not exposed to earth and weather	1.00
		Exposed to earth and weather	0.90
	GFRP	Not exposed to earth and weather	0.80
		Exposed to earth and weather	0.70

Table 9-2. Summary of sustained (service) stress limits for FRP reinforcing bars prescribed by FRP design documents in North America

Document	Material	Stress limit (% of ultimate)
Canadian Highway Bridge Design Code (CSA, 2006)	AFRP	35
	CFRP	65
	GFRP	25
Design and Construction of Building components with Fibre Reinforced Polymers (CSA, 2002)	GFRP	30
Guide for the Design and Construction of Concrete Reinforced with FRP Bars (ACI, 2006)	AFRP	30
	CFRP	55
	GFRP	20

Section 10

Specifications for Determining Durability Properties of FRP Reinforcing Bars

ISIS Canada has recently published a product certification document on Specifications for Product Certification of Fibre Reinforced Polymers (ISIS, 2006). The scope of the specifications deals with FRPs as internal reinforcement in concrete components of structures, such as bridges, buildings, and marine structures. Table 10-1 presents the test methods and specified limits for the durability properties for FRPs in the form of bars and grids. The fibres include glass, carbon and aramid fibres, and matrices include isophthalic polyester, vinylester and epoxy resins. The reader is referred to the source document for additional information.

Table 10-1. Specifications for determining durability properties of FRPs

Property	**Standard for test (refer to references for full citation)**	**Specified limits for various grades***
Void content	ASTM D 2734 Void content of reinforced plastics; or ASTM D5117 Standard test method for dye penetration of solid fiberglass reinforced pultruded stock	≤ 1%
Water absorption	ASTM D 570 water absorption of plastics	≤ 1% for D2 ≤ 0.75% for D1
Cure ratio	ASTM D 5028 Curing properties of pultrusion resin by thermal analysis (DSC)	≥ 95% for D2 bars and grids ≥ 98% for D1 bars and grids
Glass transition temperature	ASTM E 1640 Assignment of T_g by DMA; or ASTM E 1356 Assignment of T_g by DSC	DMA = 90°C, DSC = 80°C for D2 DMA = 110°C, DSC = 100°C for D1
Alkali resistance in high pH solution (without load)	ACI 440.3R-04, Test Method B.6, Accelerated Test Method for Alkali Resistance of FRP Bars; or CSA-S806-02, Annex O, Test Method of Alkali Resistance of FRP Rods	Tensile capacity retention ≥70% for D2 Tensile capacity retention ≥80% for D1
Alkali resistance in high pH solution (with load)	ACI 440.3R-04, Test Method B.6, Accelerated Test Method for Alkali Resistance of FRP Bars; or CSA-S806-02, Annex O, Test Method of Alkali Resistance of FRP Rods	Tensile capacity retention ≥60% for D2 Tensile capacity retention ≥70% for D1
Creep rupture strength	ACI 440.3R-04, Test Method B.8, Test Method for Creep Rupture of FRP Bars; or CSA-S806-02, Annex J, Test Methods for Creep of FRP Rods	Creep rupture strength: ≥35% UTS (Glass) ≥75% UTS (Carbon) ≥45% UTS (Aramid)
Creep	ACI 440.3R-04, Test Method B.8, Test Method for Creep Rupture of FRP Bars; or CSA-S806-02, Annex J, Test Methods for Creep of FRP Rods	Report creep strain values at 1000 hr, 3000 hr and 10000 hr
Fatigue strength	ACI 440.3R-04, Test Method B.7, Test Method for Tensile Fatigue of FRP Bars or CSA-S806-02, Annex L, Test Method for Tensile Fatigue of FRP Rods	Fatigue strength at 2 million cycles: ≥35% UTS (Glass) ≥75% UTS (Carbon) ≥45% UTS (Aramid)

* Depending on the durability properties defined in Table 10.1, FRPs with high durability shall be classified as D1, and FRPs with moderate durability as D2. FRPs made with vinylester and epoxy shall be classified as D1 or D2 based on the requirements of Table 10.1 while FRPs made with polyester matrix shall be classified as D2.

Section 11

Case Study: Field Evaluation of GFRP Durability in Concrete

While laboratory-based experiments conducted over the past few decades have in some cases indicated that FRP materials may be susceptible to deterioration under many of the physical and environmental conditions discussed in this module, very little in-service field data are available for FRPs used in infrastructure applications. However, the little field data that is available on the durability of many FRP systems appears to indicate that the in-service performance can be much better than that assumed on the basis of laboratory testing. To begin to address this gap in knowledge, the ISIS Canada Research Network recently completed a research project to study the in-service performance of glass FRP reinforcing bars in concrete structures in Canada (Mufti et al., 2005).

To obtain samples of glass FRP reinforcing bars after up to eight years of service inside concrete structures, researchers used coring rigs to remove glass FRP reinforcing bars from five different concrete structures. The structures included in the study included:

- Joffre Bridge (Sherbrooke, Quebec);
- Crowchild Bridge (Calgary, Alberta);
- Hall’s Harbour Wharf (Hall’s Harbour, Nova Scotia);
- Waterloo Creek Bridge (British Columbia); and
- Chatham Bridge (Ontario).

These samples were subsequently studied for evidence of deterioration using a variety of sophisticated optical, chemical, and thermal techniques. Each of the techniques used and the results obtained are discussed in the following sections.

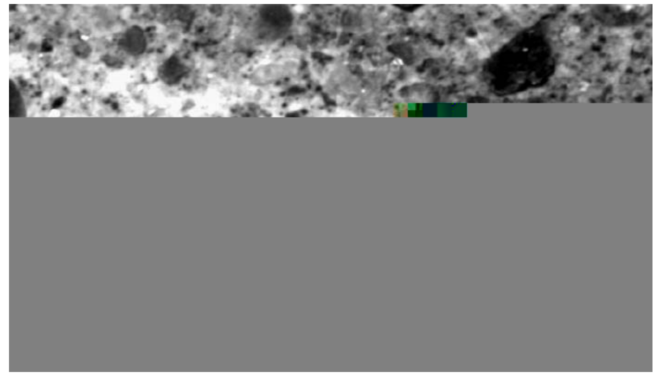

Fig. 11-1. Optical micrograph of FRP-concrete interface from Crowchild Trail Bridge (Mufti et al., 2005).

Fig. 11-2. Optical micrograph of FRP-concrete interface from Chatham Bridge (Mufti et al., 2005).

Optical Microscopy (OM)

Optical microscopy was used to examine the interface between the glass FRP reinforcing bars and the concrete. Samples of FRP bar and concrete were carefully cut from core samples and were smoothed using extremely fine grit sandpaper. The samples were then examined using optical microscopy at random locations to check for defects. The rationale for these tests was that the most likely form of damage within the alkaline environment inside concrete was alkalinity-induced damage to the FRP-concrete interface.

Examination of the interface between the glass FRP and the concrete showed no loss of bond between the concrete and the glass FRP. This is shown in Figures 11-1 and 11-2 for typical samples from two different bridges, where it can be seen that there are no gaps between the FRP and the concrete after eight years of exposure to alkalinity, freeze-thaw cycles, wet-dry cycles, chlorides, and thermal loading.

Scanning Electron Microscopy (SEM) & Energy Dispersive X-ray Analysis (EDX)

Scanning electron microscopy was used to conduct a detailed examination, at very high magnification, of the individual glass fibres in the FRP reinforcing bars. Samples were then analyzed using energy dispersive x-ray techniques, which detect changes in the chemical composition of both the polymer matrix and the glass fibres.

Electron micrographs obtained using SEM showed no sign of damage to the fibres and no reduction in the fibres’ cross-sectional area. Figures 11-3 and 11-4 show typical micrographs obtained during the study, where good bond is observed between the fibres and the matrix and the matrix and the concrete.

Fig. 11-3. Micrograph of cross-section of FRP bar from Crowchild Bridge, Calgary (Mufti et al., 2005).

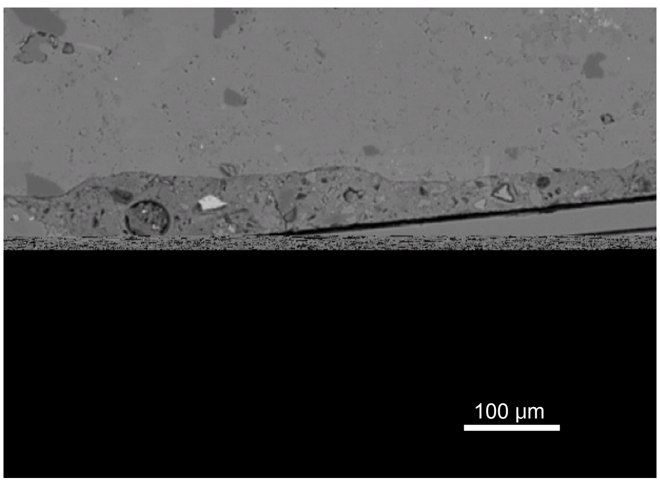

Fig. 11-4. Micrograph of longitudinal-section of FRP bar from Chatham Bridge, Ontario (Mufti et al., 2005).

Energy dispersive x-ray analyses were used to determine if any chemical changes had occurred in either the polymer matrix or the glass fibres in any of the glass FRP reinforcing bars. The goal of these analyses was essentially to determine the extent of alkali migration into the polymer matrix, since alkalis are known to be harmful to glass fibres (as discussed previously).

Without getting into the details of technique, it is sufficient to know that EDX uses a spectral technique to detect the presence of certain elements within a material, and that the presence of Sodium (Na) or Potassium (K) in the polymer matrix would be considered an indication that alkalis had migrated into the polymer matrix from the concrete pore solution. Figure 11-5 shows EDX spectra from an in-service glass FRP bar taken from one of the bridges, and clearly shows that no Sodium or Potassium are present.

Infrared Spectroscopy (IS)

Infrared spectroscopy is a technique that allowed researchers to determine the extent of alkali-induced hydrolysis of the polymer matrix, a process in which hydroxyl ions (OH^-) attack certain chemical bonds between polymer chains. The result is that the structure of the polymer is altered and the properties change.

In the present study, infrared spectroscopy was used to study changes in the amounts of hydroxyl groups present in the polymer matrix, and thus to elucidate the likelihood of matrix hydrolysis. The results of this research indicated that the hydroxyl content in the in-service specimens was very similar to control (unexposed) specimens, indicating that the hydrolysis reaction had not occurred in the glass FRP bars.

Fig. 11-5. EDX spectra from an in-service glass FRP reinforcing bar after eight years in service (Mufti et al., 2005).

Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry is a thermal measurement technique which can be used to determine the glass transition temperature (T_g) of a polymer material. Changes in the glass transition temperature of a polymer matrix material are significant in that T_g changes in the event of moisture absorption into the polymer matrix (as discussed previously). Thus, DSC studies can be used to indirectly determine if polymer materials have absorbed moisture.

In the case of the glass FRP materials considered in the current in-service durability study, no significant changes in glass transition temperature were observed between in-service and control samples of glass FRP reinforcing bar, indicating that no significant changes had occurred in the structure of the bars' polymer matrices.

SUMMARY

Test results on in-service specimens of glass FRP bars revealed that the alkaline environment within the concrete bridge decks did not appear to have any detrimental effect on the FRP materials. Specifically, no evidence of debonding, FRP microcracking, void formation, glass fibre degradation, delamination, deterioration of glass transition temperature, chemical degradation of the resin, or hydrolysis was observed. These data are extremely encouraging, and suggest that simulated durability testing of glass FRP bars in the laboratory may not be representative of actual in-service performance.

Mufti et al. (2005) offer various reasons for the apparent discrepancy between laboratory-based and in-service performance of glass FRP bars:

1. The use of high temperatures of 60 to 80ºC to artificially accelerate laboratory-based durability research studies is not representative for making service life predictions for most engineering structures.
2. Alkaline solution baths used in the laboratory to simulate the alkaline conditions within the concrete pore solution are not representative of in-service conditions. This is because the laboratory setups typically provide an infinite supply of harmful chemical compounds (leachant), whereas in concrete the rates of leachant replenishment are small due to the low porosity of concrete, the rarity of full saturation of the pores within concrete, and the fact that not all pores are connected within concrete.
3. The pH of simulated alkaline solutions in the laboratory is typically maintained at a constant value during testing, whereas in reality the pH of the concrete pore solution decreases with time.

Section 12

Durability Research Needs

Hopefully, after reading the preceding document, the reader is left with the impression that the durability performance of FRP materials is generally very good in comparison with other, more conventional, construction materials. However, it should be equally clear that the long-term durability of FRPs remains incompletely understood. A large research effort is thus required to fill all of the gaps in knowledge. Research needs with respect to the durability of FRP materials in infrastructure applications were highlighted recently in a durability gap analysis report published in the United States (Karbhari et al., 2003).

Research is required in essentially all of the areas discussed in this module; however, the Karbhari et al. (2003) gap analysis points to several key areas, as summarized below.

Moisture

The effects of under-cure and/or incomplete cure of the polymer matrix on the moisture absorption properties polymer matrices need to be studied, particularly for applications involving externally-bonded FRP materials. Also, the effects of continuous versus intermittent exposure to moisture, particularly when bonded to concrete, should be examined.

Alkalinity

Determination of rational and defensible standard alkaline solutions and alkalinity testing protocols is badly needed to allow the creation of a standard database of durability information for FRP products. Development of an understanding of alkali-induced deterioration mechanisms, both chemical and physical, is also needed. The potential synergistic effects of combined alkalinity, stress, moisture, and temperature are not well understood, particularly as they relate to creep-rupture of FRP components.

Fire

Non-destructive evaluation methods for fire-exposed composites are needed to evaluate fire damage. Fire repair strategies are also needed where fire damage is significant and localized, as is the development of relationships between tests on small scale material samples at high temperature and full-scale structural performance during fire.

Fatigue

More fatigue data are required on a variety of FRP materials, as is a mechanistic understanding of fatigue in composites in conjunction with various environmental factors such as temperature, moisture, and UV exposure. Development of a rational and defensible short term representative exposure that can be used to evaluate long-term fatigue performance of FRPs is essential.

Synergies

Research conducted to date indicates that there are potentially important synergies between most of the durability factors considered in this module. These synergies remain incompletely understood and research is needed to elucidate the interrelationships between moisture, alkalinity, temperature, stress, and chemical exposures.

Section 13

Summary & Conclusion

This educational module has provided a very brief and somewhat limited overview of the current state of knowledge with respect to the factors and environments that are currently considered important for the long-term durability of FRP reinforcing materials for infrastructure applications. It is clear from the preceding discussions that key issues regarding the durability of these materials remain unresolved, and that a considerable effort will be required to fill all of the remaining gaps in knowledge, particularly with respect to potential synergistic effects. Clearly, it is important to recognize that FRP materials, while potentially susceptible to various forms of environmental degradation, are highly durable in comparison with conventional materials such as concrete, timber, or steel. All engineering materials have weaknesses, and the task of engineers is to account for these weaknesses in ways that best take advantage of the materials' properties. FRP materials appear to be very well suited to infrastructure applications, and it is expected that they have a bright future in this area.

As FRP technology advances, new and more durable materials can be expected to be available. The durability of FRP reinforcing materials depends largely on the ability of the polymer matrix to protect the fibres and the fibre-matrix interface from distress. Emerging technologies in polymer science can be expected to further improve the durability of FRP materials well into the future.

Section 14

References & Additional Guidance

Additional information on the properties and application of FRP materials in civil engineering and construction applications can be obtained in various documents available from ISIS Canada:

DESIGN MANUALS

- ISIS Design Manual No. 3: Reinforcing Concrete Structures with Fibre Reinforced Polymers
- ISIS Design Manual No. 4: Strengthening Reinforced Concrete Structures with Externally-Bonded Fibre Reinforced Polymers.
- ISIS Design Manual No. 5: Prestressing Concrete Structures with Fibre Reinforced Polymers.

EDUCATIONAL MODULES

- ISIS Educational Module 1: Mechanics Examples Incorporating FRP Materials.
- ISIS Educational Module 2: An Introduction to FRP Composites for Construction.
- ISIS Educational Module 3: An Introduction to FRP Reinforcement for Concrete Structures
- ISIS Educational Module 4: An Introduction to FRP-Strengthening of Concrete Structures.
- ISIS Educational Module 6: Application and Handling of FRP Reinforcements for Concrete.

Due to the increasing popularity and use of FRP reinforcements in the concrete construction industry, a number of design recommendations have recently been produced by various organizations for the design of concrete structures with internal FRP reinforcement or externally-bonded FRP systems. Most of these documents provide at least summary recommendations related to the durability of FRP reinforcement and strengthening systems:

DESIGN GUIDELINES AND CODES

Canada

- CAN/CSA-S806-02: Design and Construction of Building components with Fibre Reinforced Polymers. Published by the Canadian Standards Association, Ottawa, ON. 2002.

- CAN/CSA-S6-06: Canadian Highway Bridge Design Code. Published by the Canadian Standards Association, Ottawa, ON. 2006.

United States

- ACI 440.1R-06: Guide for the design and construction Concrete Reinforced with FRP Bars. Published by the American Concrete Institute, Farmington Hills, MI. 2006.
- ACI 440.2R-02: Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. American Concrete Institute, Farmington Hills, MI. 2002.

ASTM Standards

- D 570 Standard Test Method for Water Absorption of Plastics
- D 618 Standard Practice for Conditioning Plastics for Testing
- D 695 Standard Test Method for Compressive Properties of Rigid Plastics
- D 696 Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between –30°C and 30°C with a Vitreous Silica Dilatometer
- D 790 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
- D 792 Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
- D 2584 Standard Test Method for Ignition Loss of Cured Reinforced Resins
- D 2734 Void Content of Reinforced Plastics
- D 3171 Standard Test Method for Constituent Content of Composite Materials
- D 3410 Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading

ADDITIONAL REFERENCES

The information presented in this educational module represents a compilation of information contained in the following references. These documents may be consulted for specific additional information:

- ACI 440.3R-4. 2004, Guide Test Methods for Fibre-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures. American Concrete Institute, Farmington Hills, Michigan, USA, 41 p.
- Adimi, R., Rahman, H., Benmokrane, B., and Kobayashi, K. 1998. Effect of temperature and loading frequency on the fatigue life of a CFRP rebar in concrete. Proceedings of the 2nd International Conference on Composites in Infrastructure (ICCI-98), Tucson, AZ, v. 2, pp. 203-210.
- Benmokrane, B., Wang, P., Pavate, T., Robert, M. 2006. Durability of Materials and Structures in Building and Civil Engineering. Chapter 12: Durability of FRP Composites for Civil Infrastructure Applications. Yu, C. W. (éd.), Whittles Publishing, Dunbeath, Scotland.
- Benmokrane, B. 2005. Chapter 12 – Durability of FRP, ACI Committee 440C, State-of-the-Art Report. American Concrete Institute, Farmington Hills, MI (DRAFT).
- Benmokrane, B., Wang, P., Ton-That, T.M., Rahman, H., Robert, J-F. 2002. Durability of glass fibre-reinforced polymer reinforcing bars in concrete environment. Journal of Composites for Construction, 6(3): 143-153.
- Bisby, L.A. 2003. Fire behaviour of FRP-reinforced concrete. Ph.D. Thesis, Civil Engineering, Queen’s University, Kingston, ON.
- Bisby, L.A., Green, M.F., & Kodur, V.K.R. 2005. Response to fire of concrete structures that incorporate FRP. Progress in Structural Engineering and Materials, 7: 136-149.
- Chen, Y., Davalos, J. F., Ray, I. 2006. Durability Prediction for GFRP Bars Using Short-Term Data of Accelerated Aging Tests. Journal of Composites for Construction, 10(4): 279-286.
- Chin, J., Aouadi, K., Haight, M.R., Hughes, W.L., Nguyen, T. 2001. Effects of Water, Salt Solution and Simulated Concrete Pore Solution on the Properties of Composite Matrix Resins Used in Civil Engineering Applications. Polymer Composites, 22(2): 282-297.
- Chin J.W., Nguyen, T., Aouadi, K. 1997. Effects of environmental exposure on fiber-reinforced plastic (FRP) materials used in construction. Journal of Composites Technology and Research, 19(4): 205-213.
- CAN/CSA-ISO 9001-00. 2000. Quality Management Systems - Requirements (adopted ISO 9001:2000, third edition), 23 pages.

- ISIS 2005. Excellent performance of GFRP in concrete. Intelligent Sensing for Innovative Structures Canada, Winnipeg, MB, URL: http://www.isiscanada.com/latest/latest.htm#GFRP, accessed Aug. 6, 2005.
- ISIS 2006. Specifications for Product Certification of Fibre Reinforced Polymers (FRPs) as Internal Reinforcement in Concrete Structures, ISIS Product Certification of FRP Materials, Product Certification #1, September, 2006.
- International Organization for Standardization, ISO 9001-00. 2000. Quality Management Systems—Requirements, International Organization for Standardization, Geneva, Switzerland.
- Karbhari, V.M. 2003. Durability of FRP Composites for Civil Infrastructure: Myth, Mystery, or Reality. http://www.cosacnet.soton.ac.uk/ ACIC2002/Wednesday/w0850karbhari.pdf
- Karbhari, V.M., Chin, J.W., Hunston, D., Benmokrane, B., Juska, T., Morgan, R., Lesko, J.J., Sorathia, U. and Reynaud, D. 2003. Durability gap analysis for fiber reinforced composites in civil infrastructure. Journal of Composites for Construction, 7(3): 238–247.
- Liao, K., Schultheisz, C.R., Hunston, D.L. and Brinson, L.C. 1998. Long-term durability of fiber-reinforced polymer-matrix composite materials for infrastructure applications: A review. Journal of Advanced Materials, 30(4): 3-40.
- Micelli, F. and Nanni, A. 2004. Durability of FRP rods for concrete structures. Construction and Building Materials, 18: 491-503.
- Mufti, A.A., Onofrei, M., Benmokrane, B., Banthia, N., Boulfiza, M., Newhook, J., Bakht, B., Tadros, G. and Brett, P. 2005. Durability of GRFP Reinforced Concrete in Field Structures. Proceedings of the 7th International Symposium on Fibre Reinforced Polymer Reinforcement for Reinforced Concrete Structures (FRPRCS-7), Kansas City, MO.
- Murphy, K., Zhang, S., and Karbhari, V. M. 1999. Effect of concrete based alkaline solutions on short term response of composites. Proc., 44th Int. SAMPE Symposium and Exhibition, L. J. Cohen, J. L. Bauer, and W. E. Davis, eds., Society for the Advancement of Material and Process Engineering, Long Beach, Calif., 2222–2230.
- Sorathia, U., Dapp, T. and Beck, C. 1992. Fire performance of composites. Materials Engineering, 109(9): 10-12.
- Sorathia, U., Ohlemiller, T., Lyon, R., Riffle, J. and Schultz, N. 2001. Chapter 9: Effects of fire gap analysis for durability of fibre reinforced polymer composites in civil infrastructure. American Society of Civil Engineers, New York, NY, pp. 100-121.
- Shao, Y., Kouadio, S. 2002. Durability of Fiberglass Composite Sheet Piles in Water. Journal of Composites for Construction, 6(4): 280-287.
- Tong, L., White, J.R. 1996. Photo-oxydation of thermoplastics in bending and in uniaxial compression. Polymer Degradation and Stability, 53: 381-396.
- Torres-Acosta, A.A. 2002. Galvanic Corrosion of Steel in Contact with Carbon-Polymer Composites. I: Experiments in Mortar. Journal of Composites for Construction, 6(2): 112-115.
- Weitsman, Y.J., and Elahi, M. 2000. Effects of fluids on deformation, strength and durability of polymeric composites – an overview. Mechanics of time-dependent materials, 4: 107-126.