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Fiber-Reinforced Polymer's Long-Term Performance and Durability as a Novel Civil Engineering Material

Prashant Kuri
Lecturer / Department of Civil Engineering, Government Polytechnic -Athani

ABSTRACT
Fiber-reinforced polymer (FRP) composites have become more and more popular in civil engineering applications in recent years, ranging from all-composite bridge decks to columns, beams, and slabs. However, it is currently acknowledged that the most important area of research is how long-lasting FRP is, particularly in hard environmental conditions. It is challenging for professional civil engineers and designers to regularly use FRP composites due to the absence of an extensive database on the durability of FRP materials. The most important study on the durability performance of FRPs used as internal reinforcement in concrete members has been carried out and published, and it is presented in this publication. In the past twenty years, a great deal of research has been done on its durability. A thorough analysis of the literature will be provided and discussed, covering topics such as degradation mechanisms, accelerated tests for long-term performance, and how environmental factors affect FRP durability. We'll also examine some models for predicting the service life of FRP materials.
Keywords: FRP, reinforcement, durability Highway Administration, Fiber

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I. INTRODUCTION

As illustrated in Fig. 5.1a, reinforced concrete (RC) constructions frequently fail because of steel reinforcement corroding when exposed to corrosive fluids. In the USA, Canada, and most of Europe, the costs of repairs and restorations make up a sizable portion of overall national infrastructure spending. According to a report by the Federal Highway Administration (FHWA) of the United States (US), corroded steel reinforcing will necessitate an annual investment of $20.5 billion to eliminate the nation's backlog of bridge deficiencies by 2028 [1]. Canada's municipal infrastructure deficit, which accounts for 70% of the nation's overall infrastructure, was valued at $60 billion in 2004 and is predicted to increase by $2 billion annually. Fiber-reinforced polymer (FRP) reinforcement is a relatively new way to combat the corrosion of steel reinforcement in traditional building materials. Over the past 20 years, FRPs have become more and more popular in civil engineering because of their high strength, low weight, and resistance to corrosion [2]. Applications for FRP composite materials in civil infrastructure are growing in popularity. These materials are made of stiff, strong fibers like glass, carbon, and aramid that are impregnated with polymeric resins like polyesters, vinyl esters, and epoxies.

Furthermore, the long-term performance and durability of FRP reinforcement, particularly in severe settings, inspire designers and civil engineers to adopt FRP composite materials in concrete buildings. Typical GFRP reinforcement and its application in a concrete deck slab are depicted in Figures 5.1b and 5.2, respectively. Even after composite bars' structural soundness has been certified, the industry still requires long-term durability data on the material to fully realise the promise of integrating FRP into infrastructure applications.

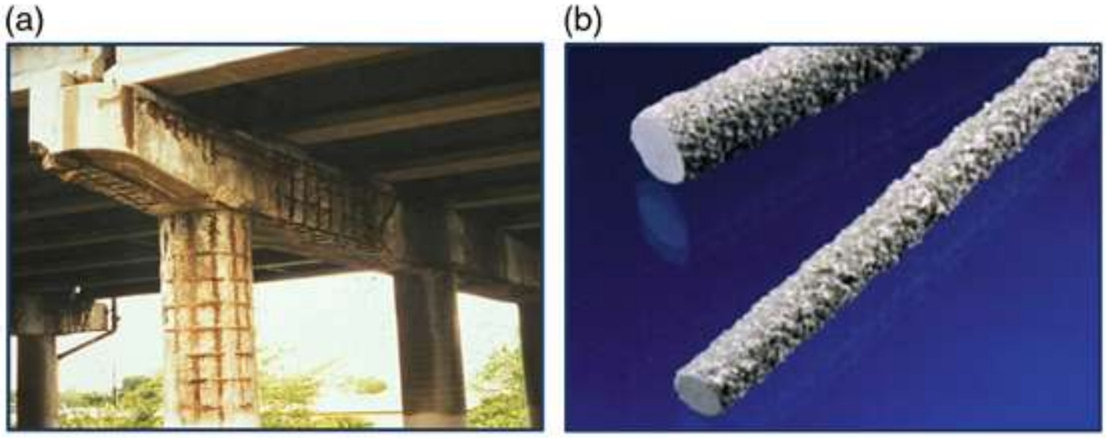

Figure No. 1 - (a) Steel corrosion in concrete bridge and (b) sand-coated GFRP bars been carried out on the longevity of FRP composites that come from the military, aerospace, and chemical industries. However, not much research has been done on the longevity of FRP composites in applications related to civil infrastructure. Recent investigations on the durability performance of fiber-reinforced polymer (FRP) composites used as internal and external reinforcement for concrete structures are presented in this study. The primary subjects of investigation pertain to how different environmental factors, including relaxation, moisture creep, and alkalinity, affect FRP reinforcement. Numerous studies have been conducted on most of these criteria, and the findings are available elsewhere [6].

II. DURABILITY CONCERNS

The performance of FRP materials can deteriorate under the influence of hostile environments, resulting in a loss of the materials' strength qualities, even though they are noncorrodible by nature and have a higher tensile strength than traditional steel reinforcing bars. According to the literature, FRP performance degrades because of prolonged loading, moisture, temperature changes, or alkalinity (Robert [3]; Robert and Benmokrane [4]; Benmokrane [5]). The kind of fibre and resin, the production process (curing rate, thermal microcracks, porosity, non-impregnated fibres, void content), and the exposure conditions all affect how much deterioration occurs [1]. Furthermore, the combined effects of FRP composites, the interface, concrete, and different mechanical and environmental conditions make it more difficult for FRP-reinforced concrete structures to perform over time. As a result, evaluating the FRPs' endurance in concrete structures is a multifaceted and intricate process. The numerous durability features of FRP composites, FRP-reinforced concrete elements, and the bond behavior of FRP in concrete are summarized in the sections that follow.

III. MAIN PARAMETERS AFFECTING THE DURABILITY OF INTERNAL FRP REINFORCEMENT

As internal reinforcement, FRP bars are made from a variety of fibre types, including glass, carbon, aramid, and basalt (BFRP). Fundamental elements include fibre type and volume percentage, resin type, fiber-matrix interface morphology and adhesion, exposure environment severity, and fabrication method are the main determinants of the extent of damage or deterioration to internal FRP reinforcement. The majority of FRP bars are made of E-glass fibres, which are more prone to deterioration in severe environments such dampness and alkalinity than carbon fibres, which are comparatively inert in these conditions. Conversely, aramid fibres are extremely they can withstand impact and abrasion, but they are vulnerable to UV light, moisture, and creep. Having an appropriate resin to shield the fibres is essential for proper performance. Numerous factors, including the resin components, their unique characteristics and ratios, and the curing circumstances and duration, affect how long the resin system lasts.

3.1: EFFECT OF MOISTURE

The impact of fluids on the performance of FRP composites has been one of the most researched areas in relation to FRP durability in recent decades. Ben Daly [6] demonstrated that the presence of fillers and additives in the matrix may have an impact on the moisture-diffusion process in pultruded composites and the saturation level reached. It has been demonstrated that the chemical structure, interface, and manufacturing method of the matrix regulate the sorption rate.

To improve the interface zone by employing proper sizing chemistry, manage the diffusion process by utilizing resin matrices with reduced permeability [7], or choose an appropriate molding method to reduce void content, a great deal of research has been done. Furthermore, a decline in Tg or chemical attack from moisture intrusion might weaken the resin. Fluids therefore have an impact on major matrix characteristics, such the transverse strength of FRP, and these characteristics deteriorate faster as exposure time and temperature increase.

Physical and chemical assaults make glass fibers vulnerable to fluid intrusion. This research area has been the subject of much investigation [13]. Although fluid infiltration has no effect on carbon fibers, it typically has an impact on the resin matrix, which lowers the composite's performance. Since the fibers in unidirectional carbon composites are particularly dominant and unaffected by fluids, this typically results in decreased compressive and shear strength with minimal effect on tensile strength [11]. Most fluids' effects on aramid fibres occur at higher temperatures. According to reports, AFRP composites soaked with water lose up to 55% of their flexural strength when under stress and during wet/dry thermal cycles, and 35% at room temperature.

3.2: DEGRADATION MECHANISM OF GFRP BARS IN ALKALINE ENVIRONMENTS

The pH range of 12 to 13 indicates the significant alkalinity of the concrete environment. Glass fibers suffer from increased embrittlement and a loss of hardness and strength in this alkaline environment. Glass and aramid fibers are less resistant to alkali than carbon fibers. The concentration of hydration products between individual filaments and chemical attack are the two mechanisms that combine to degrade glass fibers. Calcium hydroxide nucleation on the fibre surface causes embrittlement of the fibers. Hydroxylation caused pitting and roughness on the fiber surface, which decreased the fiber's qualities while wet. Furthermore, the glass fibers are severely harmed by the calcium, sodium, and potassium ions present in the concrete pore solution. As a result, the combination of alkali salts, pH, and moisture causes glass fiber deterioration in addition to the high pH level. In contrast, alkaline environments cause aramid fibers to lose strength. When Kevlar 29 is exposed to a 10% sodium hydroxide solution for 1000 hours, its strength decreases by 74%. Water temperatures up to boil and alkaline solutions at any concentration are not supposed to have an impact on carbon fibers [12]. They were, however, resistant to alkaline solutions at all concentrations and temperatures up to boiling, according to Judd [1]. After 6168 hours of immersion in a 50% sodium hydroxide solution, carbon tows demonstrated that the strength qualities varied by only 15%. High pH solutions and alkali salts may migrate through resin (or through voids, cracks, or interfaces between fiber and matrix) to the fiber surface, even though a suitable resin matrix (vinyl ester, epoxy) offers some protection to fibers against alkaline degradation. Studies on the effects of alkalis and moisture on E-glass/vinyl ester composite strips at different temperatures (22, 40, 60, and 80 degrees Celsius) were carried out by Chu [13]. Tensile strength degradations ranged from 35% to 62% of the original value.

Two GFRP kinds (E-glass/vinyl ester) were the subject of a durability study by Kim [14] that lasted up to 132 days at 25, 40, and 80 C under a variety of environmental conditions, including moisture, chloride, alkali, and freeze-thaw cycling. We can conclude that the tensile strength of GFRP bars was more affected by an alkaline environment than by any other environmental condition. Robert [4] investigated the microstructural, mechanical, and durability characteristics of unstressed GFRP bars in saline and alkaline solutions. The effect of seawater and deciding salts on GFRP bars was simulated using this conditioning. The findings demonstrated that the concrete-wrapped GFRP bars submerged in tap water or saline solution had no discernible impact on their long-term durability; instead, the GFRP bars in saline solution demonstrated very good durability. Recent research on the durability performance of carbon-fiber-composite cable (CFCC) tendons subjected to high temperatures and an alkaline environment was carried out by Benmokrane [1]. For 1000, 3000, 5000, and 7000 hours, specimens were exposed to alkaline solutions at higher temperatures (22, 40, 50, and 60 degrees Celsius).

After 7000 hours of conditioning at 60 degrees Celsius, the test results showed a 7.17% decrease in tensile strength. Benmokrane [2] recently evaluated the mechanical and physical characteristics of GFRP bars composed of three different kinds of reins: epoxy, isophthalic polyester, and vinyl ester. The GFRP bars were submerged in an alkaline solution at 60C for 1000, 3000, and 5000 hours to conduct the investigation. According to the test results, the polyester GFRP bars had the lowest strength characteristics following conditioning, while the vinyl ester and epoxy GFRP bars had the best strengths and the lowest rate of deterioration.

3.3: EFFECT OF FREEZE AND FREEZE/THAW CYCLES

Fibers are not impacted by freezing or freeze/thaw exposures, but the resin and the fiber/resin contact may be. Many studies on this topic focused on materials used in aircraft. According to the research, pultruded FRP composites are not significantly affected by freezing and thawing [15]. Due to matrix stiffening and a mismatch in the thermal expansion coefficients of the matrix and resin, as well as between the FRP and concrete, complicated residual stress typically develops in FRP composites at low temperatures. Because of crystal formation and elevated salt concentration, the presence of deciding salts under wet conditions followed by freeze/thaw cycling might result in microcrack formation and slow degradation. The durability of FRP bonding to concrete elements subjected to 250 freeze/thaw cycles and continuous load was examined by Alves [16]. The combined conditions strengthened the GFRP-concrete bond, according to the test results.

IV. DURABILITY OF GFRP-REINFORCED CONCRETE IN FIELD STRUCTURES

To gather field data on the endurance of GFRP in concrete exposed to natural conditions, ISIS Canada, a Canadian Network of Centres of Excellence, initiated a significant study in 2004. The study's goal was to present performance information on a GFRP that has been applied to several Canadian structures. The GFRP's chemical and physical compositions were examined at the microscopic level after concrete cores containing the material were taken out of several exposed structures that were between five and eight years old. Five ISIS Canada field demonstration structures were selected (Fig. 5.3). These structures were constructed in five different provinces and exposed to a variety of environmental conditions: Hall's Harbour Wharf in Nova Scotia, Joffre Bridge in Quebec, Chatham Bridge in Ontario, Crowchild Trail Bridge in Alberta, and Waterloo Creek Bridge in British Columbia. Numerous environmental factors that are typical of the Canadian climate are reflected in their selection. Independent microanalyses were conducted by three study teams from four Canadian universities on the concrete encircling the GFRP. They employed a variety of analytical techniques to (a) determine whether alkalis had attacked the GFRP in the concrete field structures and (b) compare the composition of the GFRP extracted from in-service structures with control specimens that were preserved from the projects and shielded from the concrete environment. Direct comparisons were performed using "virgin" GFRP rods that had been stored in a controlled laboratory environment. The findings show that none of the field demonstration buildings in this study showed signs of GFRP deterioration, and that the alkalinity of the concrete did not cause any chemical degradation processes within the GFRP.

Figure No. 2 - Pictures from the five field demonstration projects considered

V. ENVIRONMENTAL REDUCTION FACTORS (CE) FOR GFRP BARS

The inclusion of design recommendations for shear design, indirect deflection control, and flexural crack management of concrete structures reinforced with FRP coincides with the upgrading of ACI 440 [17]. According to the ACI 440 design code [17], the design tensile strength of GRPP bars is determined by Eq. 5.1: f fu ¼ CE:ffu∗ffu ¼ CE:ffu∗ ð5:1Þ, where ffu and ffu* stand for the GFRP bar's design tensile strength and guaranteed tensile strength, respectively. We see that the environmental reduction factor (CE) for GFRP bars in the ACI 440 [17] design standard is suggested to be 0.7 or 0.8 for concrete elements exposed to and not exposed to weather and soil, respectively.

Eq. 5.2: CE ¼fpred = ffu∗ ð5:2Þ, where fpred ¼ predicted tensile strength of GFRP bar at 75 or 100 years, was used to calculate the CE values based on long-term durability databases from the literature [10] to meet the ACI committee requirements regarding the CE values for the long-term durability of GFRP bar in concrete. Eq. 5.2 was used to evaluate the factor (CE) based on experimental and anticipated tensile strength results found in the literature. As a result, using the guaranteed tensile strength (Eq. 5.2), a new value for the factory (CE) value was determined. It is evident that the reduction factor (CE) values that were computed were greater than those found in ACI 440 [17]. For this reason, we advise using a reduction factor (CE) of 0.90.

VI. CONCLUSION

Up till now, the use of FRP reinforcement in various structures has shown great success. When compared to other, more traditional building materials, the durability performance of FRP materials is often extremely good, according to the study study. Nevertheless, nothing is known about FRPs' long-term endurance. Therefore, to close the information gaps, more study on the durability of FRPs is needed.Researchers have presented various mathematical equations that describe the relationship between strength retention and ageing time, each of which is based on a different theoretical framework. There are typically four different kinds of FRP strength models, and the Arrhenius equations serve as the foundation for all the prediction processes for those models. There are primarily two methods for predicting the performance of FRP bars, according toassessing "strength retention" or "moisture absorption." The four popular mathematical models found in the literature are briefly described here. The "moisture absorption" hypothesis

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