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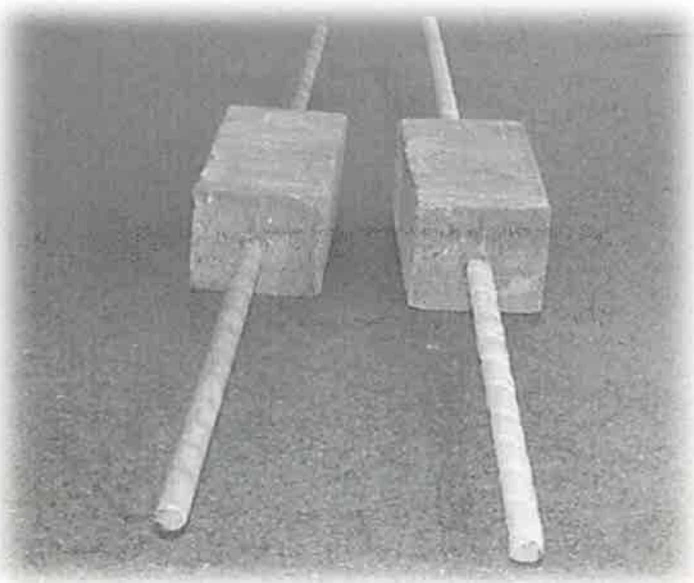

Durability of FRP Reinforcement in Concrete

- Literature Review and Experiments

VALTER DEJKE

Department of Building Materials
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2001

Abstract

During the latest decade there has been an important increase in the use of FRP (Fibre Reinforced Polymers) as concrete reinforcement in the construction industry. The most obvious benefit of using FRP for concrete reinforcement is that it does not corrode in the same way as steel, which makes it an interesting reinforcement option for concrete structures in severe environments. However, FRP is prone to deteriorate due to other degradation mechanisms than those for steel. The high alkalinity of concrete, for instance, is a possible degradation source. Other potentially FRP aggressive environments are sea salt, de-icing salt, freeze-thaw action, UV-light and fresh water/moisture. This licentiate thesis includes an update of knowledge regarding durability of FRP reinforcement in relevant environments and an overview of current research activities in this field. Although a great deal of research has been addressing the durability of FRP reinforcement, very few quantitative predictions of material property deterioration have been reported.

This thesis particularly focuses on GFRP reinforcement. GFRP is known to deteriorate in the environment of concrete. However, of the FRP types available GFRP is the cheapest and consequently has the highest potential of being cost effective. Hence, there is a need for reliable estimations of the rate of deterioration of GFRP in the environment of concrete. An important part of the work described in this thesis have been to gain a better understanding of the degradation mechanisms of GFRP reinforcement in concrete and to make a quantitative service life prediction for this material in real applications. The work includes a literature review of degradation mechanisms of GFRP in concrete, a theoretical discussion of possible degradation modes, durability experiments and formulation of service life prediction models.

The experimental work involves exposure of four GFRP types in concrete, alkaline solution and water at 20, 40, 60 and 80°C. After exposure the specimens were examined, using several analysis methods, to investigate the environmental effects on mechanical and physical properties. Altogether approximately 1400 specimens were included in the experimental programme.

Of the GFRP bars tested, systems containing E-glass and vinyl ester appear to have better overall durability than the other systems. The tensile strength retention after approximately 1.5 year in moisture saturated concrete at 60°C and the ILSS retention after approximately one year under the same conditions were 57% and 96% respectively for the bar having the best environmental resistance.

Two models for strength retention predictions have been formulated . One of them assumes that the rate of strength retention at different temperatures can be described by the Arrhenius equation. Using this approach it is possible to transform exposure time under accelerated conditions to time in a real application. Thus 1.5 years at 60°C correspond to approximately 50 years in outdoor conditions in the south of Sweden (mean annual temperature, 7°C). The other predictive model takes account of any differences in the influence of the temperature on the rate of transport mechanisms within the composite and on the chemical reactions leading to degradation.

A general conclusion from this work is that the use of FRP reinforcement can be recommended for concrete structures of arbitrary required service lives provided a proper strength reduction factor is used to take account of the deterioration of the material. Such a strength reduction factor should be separately determined for every application, and based the deterioration rate controlling factors including moisture conditions, temperature, stress level and required service life.

Contents

Part A

Durability of FRP reinforcement in concrete
-A literature review

Summary

During the latest decade there has been a substantial increase in the use of FRP (Fibre Reinforced Polymers) as concrete reinforcement in the construction industry. FRP consists of continuous fibres, usually aramid, carbon or glass, in a polymer matrix, usually consisting of polyester, vinyl ester or epoxy. The mechanical properties are quite different from those of steel. Generally, FRP has lower weight; lower Young's modulus but higher tensile strength than steel. In addition, the stress-strain curve is straight until failure, giving the material a brittle failure mode.

The most important benefit of FRP reinforcement is perhaps the fact that it does not corrode in the same way as steel, which makes it an interesting reinforcement option for concrete structures in severe environments. Other applications are structures where reinforcement with non-metallic properties is required (for example in the surroundings of some medical equipment) or where a member must have a high strength to weight ratio. Another important advantage of this material is that it is easy to handle, which reduces the application time and total cost. This is a great benefit especially in repair/retrofit works.

However, the FRP material is prone to deteriorate due to other degradation mechanisms and durability is probably the most important criterion for the implementation of FRP reinforcement for concrete in the construction industry. Structural engineers have to be convinced that FRP reinforcement will have an acceptable lifetime before this kind of reinforcement can be used on a large scale. The durability of FRP for concrete reinforcement has therefore been a pressing issue in recent years and has been the subject of many research activities now in progress in several countries all over the world.

In the present part of this report (Part A), the durability of FRP used as concrete reinforcement is discussed. The objective has been to summarise the current research and knowledge on the subject, and to identify areas where more research is needed to clarify the uncertainties associated with the durability of FRP. Examples of potentially aggressive environments and conditions discussed in this part of the report are: water and moisture, salt, alkali, freeze-thaw actions, ultraviolet rays, thermal actions. In addition, different service life prediction methods that have been proposed are discussed. The information in this part of the report is mainly obtained from proceedings from FRP related conferences from the year 1997 and later.

To evaluate the durability of FRP reinforcement, a lot of ageing experiments have been performed worldwide. Since the effects of natural ageing cannot be achieved in a reasonable time, the experiments are generally accelerated to a great extent by using elevated temperatures in the exposure environments.

From the literature review it can be concluded that more knowledge is needed at different levels. There are some specific topics where further research is required. These topics are discussed in the report. Furthermore, there are some aspects which are appropriate for research activities in a general sense. An important issue is that no "standard durability test method" exists. This makes the results obtained by different researchers difficult to compare. However, the most important general problem is

probably the uncertainty associated with the transformation of accelerated test results into real exposure time. The "real" lifetime is sometimes determined by extrapolation of deterioration data from real exposure, or by using a shift factor determined by relating deterioration under accelerated conditions to deterioration under real application environments. Nevertheless, the need of verification by following up the real ageing and related deterioration is always emphasised.

To achieve more reliable lifetime data, the degradation mechanism for different FRP systems must be surveyed and more closely connected to the lifetime prediction. This consideration is valid for the majority of durability areas, but the resistance of FRP to alkali could be said to be the most basic issue since alkali will always be present when FRP are used as concrete reinforcement.

Part B

Durability of GFRP reinforcement in concrete -Literature review, experiments and service life prediction

Summary

In Part B the focus is put on the durability of GFRP in concrete. The aims have been to gain a better understanding of the degradation mechanisms, and to make a quantitative service life (strength retention) prediction for GFRP reinforcement in concrete. The work has involved literature reviews as well as experiments and the development of service life prediction models.

Four different GFRP bars have been exposed to concrete, alkaline solution and water, at 20, 40, 60 and 80°C to speed up the degradation. After exposure the specimens have been examined to investigate the environmental effects on mechanical and physical properties. Altogether approximately1400 specimens were included in the experimental programme.

Tensile strength and pullout strength have been tested, as these two properties are fundamental for concrete reinforcement. In addition, ILSS (Interlaminar Shear Strength) tests have been conducted. Weight gain measurements were conducted for specimens exposed to water and simulated concrete pore solution. TGA (Thermo Gravimetric Analyses) were performed to determine the fibre volume fraction in the composites. Samples were also analysed using *SEM/EDX* (Scanning Electron Microscopy/Electron Disperse X-ray) and *LA-ICPMS* (Laser Ablation Inductive Coupled Plasma Mass Spectroscopy) to detect signs of degradation or alkali ingress taking place in the material.

According to the experimental results the GFRP bars containing E-glass and vinyl ester appear to have better overall durability than the other systems tested. The tensile strength retention after approximately 1.5 year in moisture saturated concrete at 60°C and the ILSS retention after approximately one year under the same conditions were as follows: 41% and 90% for FIBERBAR (E-glass/vinyl ester), 57% and 96% for the Grey bar (E-glass/vinyl ester), 45% and 37% for the Yellow bar (AR-glass/vinyl ester) and 53% and 0% for the Green bar (AR-glass/polyester).

Two models for strength retention predictions have been formulated . One of them assumes that the rate of strength retention at different temperatures can be described by the Arrhenius equation. Using this approach it is possible to transform exposure time under accelerated conditions to time in a real application. 1.5 years at 60°C corresponds to approximately 50 years in outdoor conditions in the south of Sweden (mean annual temperature, 7°C). The other predictive model takes account of any difference in the influence of the temperature on the rate of transport mechanisms within the composite and on the chemical reactions leading to degradation.

Thermosetting resins are known to be semi permeable allowing water but not alkali ions to penetrate. However, according to test results obtained within this project alkali penetration can actually be detected in GFRP composites (after exposure for 6 months in alkaline solution at 60°C), although no alkali penetration could be detected in the pure matrix material used in the composite after the same exposure. It is believed that alkali transport occurs through micro-cracks or possibly in the fibre/matrix interface.

Furthermore, the rate of weight gain in the GFRP composites examined is higher than the theoretical, determined from the rate of weight gain in the polymer matrix and the fibre volume fraction. This is another indication that micro-cracks (or porous fibre/matrix interface regions) exist in the composites, in which the transport of alkali ions can take place. However, alkali ingress could not be detected in GFRP bars having an undamaged polymer surface layer. It therefore appears as if such polymer layers actually serve as an effective barrier to alkali ion penetration, and produce an improvement in durability.

In this durability project the GFRP bars exposed under various environmental conditions have not been subjected to any mechanical stress during the exposure. Furthermore, the exposure conditions used in this project do not involve any cycling (in temperature or moisture level), and hence any effects caused by such cycling in exposure conditions are not covered by this investigation. Furthermore, in most real applications the concrete is not moisture saturated and hence, the deterioration probably takes place at a lower rate under real applications than under the experimental conditions. These aspects have to be taken into consideration when judging the results reported from this study.

A general conclusion from this work is that the use of GFRP reinforcement can be recommended for concrete structures of arbitrary required service lives provided a proper strength reduction factor is used to take account of the deterioration of the material. Such a strength reduction factor should be separately determined for every application, and based the deterioration rate controlling factors including moisture conditions, temperature, stress level and required service life.