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Long term durability of pultruded polymer composite rebar in concrete environment

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ABSTRACT

Pultruded glass fibre reinforced polymer (GFRP) composite rebar was immersed in alkaline concrete environment for 0, 1, 2, 3, 4, 6, 14 and 24 months at 60 °C to evaluate its durability in concrete structure. Moisture absorption of the rebar was found to be only 0.76%. It was also found that both the glass transition temperature (T_g) and the short beam shear strength were retained by about 91.5%; and the above properties were remained almost unchanged during the ageing period from 1 month to 24 months. Design tensile strength and tensile elastic modulus of the rebar were retained by 100% after 24 months exposure in concrete environment. Degradation of GFRP rebar was not evident in the FT-IR results as supported by scanning electron micrographs and energy dispersive X-ray analysis. Moisture absorption was found to be a critical factor that controlled thermal and mechanical properties of GFRP rebar.

1. Introduction

The use of GFRP composite bar as reinforcement for concrete is still a relatively new technology, and currently there is no standard for the durability properties of GFRP rebar. Handful of information regarding the durability of GFRP rebar in concrete, a highly alkaline environment, is one of the issues limiting the acceptance of this material in civil engineering applications.

Typically, GFRP rebar consists of reinforcing glass fibre which is the hardest, strongest and stiffest component, embedded in a continuous polymer matrix (e.g. polyester, vinyl ester and epoxy resins). The main functions of the matrix are to transmit externally applied loads to the reinforcement and to protect the latter from external mechanical and environmental damages [1]. GFRP rebar do not corrode by electro-chemical reaction as in rusting of steel; however, their durability primarily depends on the constituent materials (e.g. glass and resin types), manufacturing process and structural integrity of the rebar (e.g. no internal crack). Also, strength and stiffness of GFRP rebar may increase, decrease, or remain the same, depending on the particular material and environmental conditions [2].

The polymer matrix of GFRP rebar provides a chemical barrier for the glass fibres from the corrosive effects of moisture and alkalis in concrete. In moist environment, water molecules react with the ester group (—O—CO—) of polymer matrix (e.g. polyester resin) which cause irreversible chemical change by hydrolytic reaction and diminishes toughness and fracture strain. Vinyl ester resin is less vulnerable to hydrolytic reaction because of less ester group present in the polymer molecule compared to polyester resin. Epoxy resin is also resistant to chemical attack; however, price of this resin is reasonably higher than the vinyl ester resin. So vinyl ester resin is being commonly used for manufacturing of GFRP rebar. Both vinyl ester resin and epoxy resin are permitted for fibre reinforced rebar products for permanent applications in concrete [3]. In the case of alkali attack to glass fibre, the chemical reaction involves a breakdown of the silica (—Si—O—Si—) network by hydroxide ions (OH^-) of concrete pore solution and eventually glass fibres lose weight and strength when they are in contact with strong alkalis. The rate of deterioration of the fibres depends on the alkalinity of the matrix (i.e. the availability of OH^- ions). Boron free E-CR glass ("Electrical" grade "Corrosion Resistant" glass) is more resistant to strong alkalis than E-glass as reported in [4]. Thus a GFRP rebar made up of chemical resistance resin (e.g. vinyl ester resin or epoxy resin) along with corrosion resistant glass is expected to be highly durable in concrete environment subject to the facts that the resin of the rebar is well cured and the rebar is free from cracks and internal flaws.

Preferably, GFRP rebar that is intended for long term use should be examined in real time and in-service environment. The required service life of concrete reinforcement is usually in the order of 50–100 years. However, the time involved is not viable and therefore, accelerated ageing (or weathering) techniques are required. The most common approach to accelerate ageing uses elevated temperature tests combined with reasonable in-service environment

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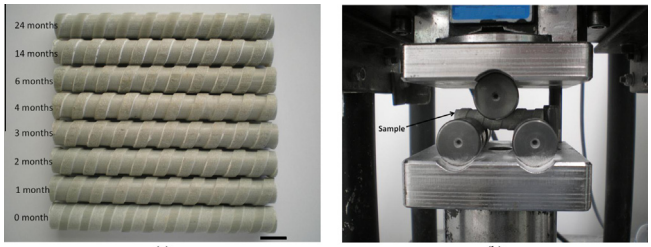

Fig. 1. Photographs of (a) alkaline aged and control rebar samples (scale = 15 mm) and (b) typical short beam shear test setup.

[5]. Short term accelerated ageing has often been extrapolated to make long term mechanical property estimates [5,6]. It has been reported that 42 days immersion of GFRP in alkaline environment (pH ≈ 13) at 60 °C would corresponds to 28 years in a real concrete structure [7]. In another report, Dejke [8] predicted that conditioning of GFRP rebar for 18 months in concrete at 60 °C corresponds to 100 years at outdoor conditions where the mean annual temperature is 7 °C.

A number of investigations have been conducted to evaluate the effects of moisture, loading, temperature, polymer matrix and different harsh environments on the properties of GFRP rebar [7,9–11]. However, there have not been many investigations that have explained properties of GFRP rebar over long periods of time, a year or longer. Objective of the entire research project, of which this work is a part, is to systematically investigate long term durability of pultruded GFRP rebar in concrete environment. In particular, this paper presents the effects of long period (24 months) alkaline ageing at elevated temperature on thermal and mechanical properties of GFRP rebar.

2. Materials and methods

2.1. Material

The GFRP rebar was received from Pultron Composites Limited, New Zealand. These threaded rebar (brand name is Mateenbar™) of 14 mm diameter (outer diameter) were made up of unidirectional roving of E-CR glass and epoxy vinyl ester resin as manufactured through pultrusion process. The GFRP rebar samples were well cured and crack free.

2.2. Methods

2.2.1. Alkali resistance test

A temperature controlled stainless steel tank was used to immerse the GFRP bars in alkaline solution for 1, 2, 3, 4, 6, 14 and 24 months at 60 °C. Typical alkaline solution was made up of 118.5 g of $Ca(OH)_2$, 0.9 g of NaOH, and 4.2 g of KOH in 1 L of deionised water [12]. The alkaline solution had a pH value of around 13, a representative pH value of mature concrete pore solution. Photograph of alkaline aged rebar samples is presented in Fig. 1a.

2.2.2. Moisture absorption test

Moisture absorption of the rebar was monitored periodically from 1 h to 17280 h (i.e. 24 months). A digital scale with accuracy of ±0.0001 g was used to weight the samples. Water uptake of three samples was recorded in each time and the average values are presented. The percentage moisture uptake was measured through gravimetric means using the following equation:

$$M(\%) = \{(W_t - W_o)/W_o\} \times 100 \quad (1)$$

where W_t is the weight of the wet specimen and W_o is the weight of the dry specimen.

Precautions were taken to remove the surface moisture from all the rebar specimens by carefully wiping them off each time before weighing.

2.2.3. Fourier transform infrared (FT-IR) spectroscopy

A Nicolet 6000 FT-IR from Thermo Scientific was used to obtain spectra of controlled and alkaline aged samples. The potassium bromide (KBr) disc sample preparation method was followed to take the infrared spectra. The samples were ground and mixed with KBr at a ratio of 1:99. Then the mixer was pressed under vacuum to form pellets. FT-IR spectra were recorded in a range of 4000–650 cm^{-1} at a resolution of 4 cm^{-1}.

2.2.4. Differential scanning calorimetry (DSC)

T_g measurement was carried out using a TA Instruments Modulated DSC 2920. About 15–20 mg sample was scanned at a heating rate of 5 °C/min from −40 to 150 °C with a modulation period of 60 s and a modulation peak of ±0.5 °C. T_g was evaluated by analysing the heat flow signal using TA Instruments' Universal Analysis software package and it was identified as the temperature at half height of the step change. Three samples of each type were tested and the average value is reported.

2.2.5. Short beam shear test

In this work, short beam shear test was performed using test configuration as described in ASTM: D4475. Typical test set-up is shown in Fig. 1b. Short beam shear strength (SBSS) was calculated using the following equation:

$$SBSS = 0.849 \times (P/d)^2 \quad (2)$$

where P is the breaking load and d is the diameter of specimen. Five samples of each type were tested and the average value is reported.

2.2.6. Tensile test

Specimen preparation and tensile test were conducted according to the guidelines as specified in ASTM: D7205/D7205M and ACI 440.3R-04 [12]. Tensile specimen for testing was prepared by anchoring two ends of the rebar in steel plugs filled with epoxy resin. The free length between the steel plugs was about 40 times of root diameter of the rebar. The tensile test was performed on 4–6 replicates of each batch using a universal testing machine (WDW-200E) fitted with 200 kN load cell. Load ramp rate was set at 667 N/s, and an extensometer of 50 mm gauge length was mounted with clips at the centre of test specimen. Load versus extension data were acquired by computer, which was also facilitated machine control. The ultimate tensile strength, elastic modulus and tensile strain were calculated using Eqs. (3), (4) and (5), respectively:

$$f_u = F_u/A \quad (3)$$

$$E_L = (F_1 - F_2)/\{(\varepsilon_1 - \varepsilon_2) \times A\} \quad (4)$$

$$\varepsilon_u = F_u/(E_L \times A) \quad (5)$$

where f_u is the tensile strength, MPa; F_u the tensile capacity, N; A the cross-sectional area of root diameter, mm^2; E_L the longitudinal modulus of elasticity, MPa; F_1 and ε_1 the load and corresponding strain, respectively, at approximately 50% of the ultimate tensile capacity, N and dimensionless, respectively; F_2 and ε_2 are the load and corresponding strain, respectively, at approximately 20% of the ultimate tensile capacity, N and dimensionless, respectively; ε_u = ultimate strain, dimensionless.