INVESTIGATING THE REVERSIBILITY OF MOISTURE UPTAKE ON THE BEHAVIOR OF A PULTRUDED POLYMER COMPOSITE USED IN CONSTRUCTION

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Keywords: glass fibre reinforced polymer, moisture absorption, desorption, chemical decomposition

Abstract

This paper presents the effects of wet/dry cycling loading on the moisture uptake behavior of a Fibre Reinforced Polymer (FRP) composite used in the civil engineering sector. FRP samples of various dimensions were cut from an 'off-the-shelf' pultruded flat sheet and conditioned in a cyclic hygrothermal environment. A series of 3 consecutive moisture absorption-desorption cycles lasting for 153 days were carried out to investigate the moisture uptake behavior of FRPs. The hygrothermal procedure consisted of immersion in 60°C distilled water until saturation and consecutively drying in a 60°C oven until equilibrium was reached. After the 1st desorption cycle, it was found that FRP samples lose a significant amount of mass due to chemical decomposition, the extent of which increases as wet/dry cyclic loading progresses. The effective mass loss leads to a subsequent significant increase in the rate of moisture uptake. Mechanical behavior of the FRPs aged at 40°C and 60°C for 224 days is examined at both 'wet' and 'dry' states to reveal the reversible and irreversible effects of moisture uptake. It was revealed that the effects of 40°C hygrothermal aging on mechanical performance are reversible when samples are dried out.

1. Introduction

The performance of FRP composites in civil engineering environments represents a key driver in their selection as construction material intended for structural applications. Pultruded FRPs (PFRPs) are commonly used materials in the civil engineering sector. Typically, PFRPs consist of E-glass fibre reinforcement (layers of unidirectional rovings and continuous filament mats) in a thermoset (e.g. polyester or vinylester) resin based matrix [1]. They are being employed as primary and secondary structural elements providing high resistance to extreme environmental conditions such as freeze-thaw, UV, etc. [2]. Compared to conventional engineering materials like steel, FRPs possess high strength and stiffness-to-weight ratios as well as flexibility in the design of complex shapes and compared to reinforced concrete structures, FRPs provide a solution against chloride ion and chemical attack. In addition to bridge engineering, civil FRPs [3] are used in a variety of other engineering applications including facades, off-shore and on-shore platforms, wind turbine blades, ladders and composite utility poles [4, 5], as well as reinforcement of concrete and steel structures [6].

In many applications, where FRPs would be exposed to the outdoor environment they will be subjected to wetting and drying cycles. The absorbtion of moisture by FRPs is considered a precursor to material degradation [1]. It is therefore, essential that an accelerated experimental regime of simulated accelerated aging process is devised, monitoring the cumulative mass loss of the components during absorption and desorption cycles and characterizing the deteriorated specimens within a suitable timeframe.

Thus far, the diffusion coefficients in the three principal directions have been determined for selectively aging conditions at 60ºC through the application of one-dimensional Fickian theory. Mechanical, viscoelastic and physico-chemical analyses (Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopic (EDS) analysis) evaluated the moisture uptake of the FRPs and verified the decomposition taking place during the aging of FRP samples after 224 days of immersion [7, 8]. EDS has showed no chemical degradation incidents on the fibre reinforcement surfaces and infrared spectroscopy revealed superficial chemical alteration in the aging matrix. Therefore, it was reported that chemical decomposition, which is simply seen as mass loss of the initial dry mass of samples, stems from the ‘weak’ fibre sizing [1, 7]. Moreover, a sensing system based on Electrical Impedance Spectroscopy (EIS) has been developed to reveal ‘true’ moisture uptake characterstics of FRPs, independent of mass loss due to decomposition effects [9]. It is of particular interest though, to assess the effect cyclic hygrothermal loading has on FRPs and the possibility to reverse the effects of aging. The results are significant for the development of durable composites exposed in wetting and drying environments, while research can be extended to loading combinations including harsh environment and extreme loading requirements.

This paper was part of an extensive study regarding the effects of moisture on the durability of polymer composites (DURACOMP project, Providing Confidence in Durable Composites, EP/K026925/1, EPSRC).

2. Background

When FRP samples are exposed to moist enviroments, moisture concentration increases with time and reaches a saturation point after an extended period of time which is always dependent on the exposure temperature, the type and thickness of the material. Generally, moisture absorption in polymer composites follows a Fickian diffusion trend [10]. However, Fickian theory is unable to describe the moisture diffusion process when significant mass loss due to chemical decomposition occurs simultaneously with moisture absorption [1]. Fig. 1 depicts 3 moisture uptake vs. time curves that are representative of a) a classical Fickian diffusion three-stage curve with no mass loss, b) a diffusion curve affected by mass loss taking place, and, c) a ‘true’ diffusion curve when mass loss takes place without affecting the moisture uptake measurements.

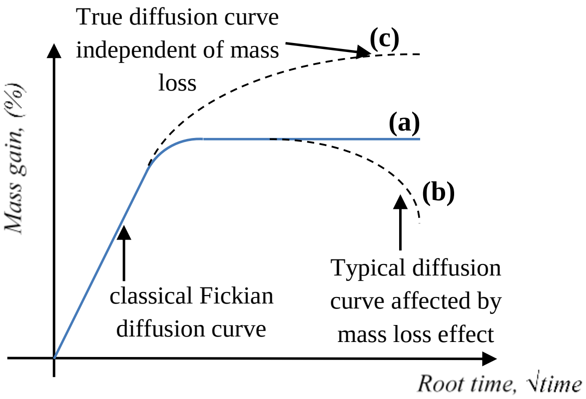

Figure 1. Representative plot of a) a classical Fickian diffusion three-stage curve with no mass loss, b) a diffusion curve affected by mass loss and c) a 'true' diffusion curve when mass loss takes place without affecting moisture uptake measurements for Mass gain (%) vs. √t [9].

Water uptake monitoring conducted via gravimetric measurements often results in behaviour matching case 'b' curves of Fig.1. It is therefore interesting to study the effect of cyclic hygrothermal loadings on the water uptake characteristics of FRPs.

3. Experimental procedure

3.1 Material

A 5-ply commercially available glass FRP pultruded profile [FS040.101.096A] was tested provided by 'Creative Pultrusions Inc., PA, USA'. The nominal thickness of the profile was approximately 6.4 mm. The outer surfaces of the laminates are covered by a protecting and non-structural polyester layer (veil) which has the dual functions of retarding moisture ingress and protecting the PFRP material from UV radiation. E-glass fibres served as the reinforcement and an isophthalic polyester resin formed the matrix of the composite. Fig. 2 shows the structure of the tested FRP material which consisted of 3 continuous strand mats (CSM) and 2 unidirectional (UD) layers with 33.3% fibre and 54.5% fibre volume fractions, respectively.

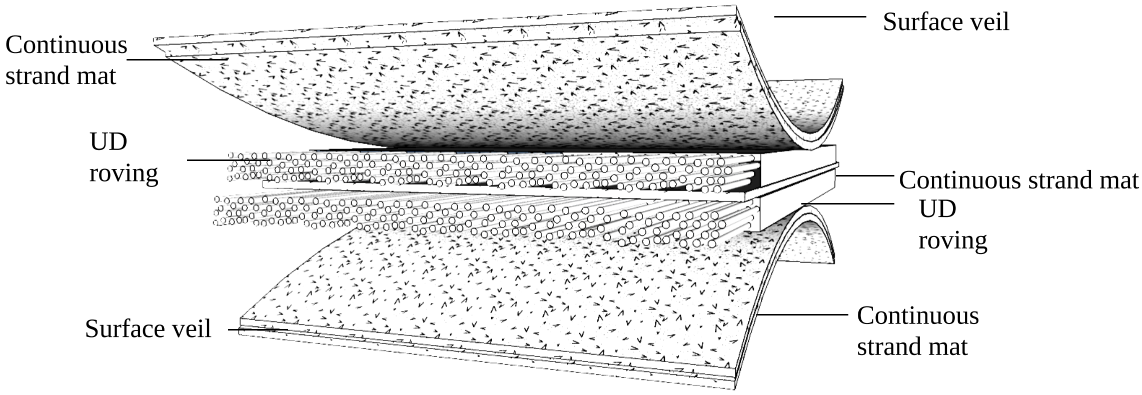

Figure 2. PFRP profile schematic representation.

3.2. Hygrothermal aging

Cyclic hygrothermal loadings were conducted on 40x40mm samples immersed in 60°C distilled water. Prior to immersion, all samples were dried in an over for 48hrs at 30°C to remove any moisture absorbed by the environment. Samples were subjected to a total of 3 absorption-desorption cycles. Moisture absorption cycles continued up until samples had gained 0.5% of mass compared to their initial dry state. Then samples were dried in an oven at 60°C until equilibrium, prior to water immersion for the next cycle. Gravimetric measurements were conducted using a digital analytical scale with ±0.001mg accuracy. Relative (*M(%)*) moisture uptake increase was determined using Eq. 1 (ASTM D5229):

$$M(\%) = \frac{M_t - M_0}{M_0} * 100\% \qquad (1)$$

where M_t is the measured moisture mass at time t and M_o the initial dry mass (reference state). Moisture uptake measurements were conducted over a period of up to 224 days [1].

3.3. Mechanical testing

In order to assess the effects of hygrothermal cyclic loadings on the behaviour of the PFRP material, ‘Plate twist’ testing was adopted. Plate twist is a standard in-plane shear test for polymer composites. During plate twisting, samples are subjected to stresses well within the elastic range and hence, the test allowed for the same samples to be repeatedly used in both wet and dry states Plate twist shear tests were conducted according to the ISO 15310 standard for testing [11]. Samples were cut in 200x200x6.4mm dimensions and subjected to water immersion at 40°C and 60°C for a period of 224 days. After aging, all samples were tested in shear in the wet state. Subsequently, samples were dried in an oven (drying temperature identical to hygrothermal aging temperature), until equilibrium was reached. After drying, samples were then tested in their dry state.

4. Results and discussion

Fig. 3 displays a representative 3-cycle moisture absorption-desorption curve. As can be seen, it takes less days for the samples to reach 0.5% mass gain, during the 2nd and significanlty less during the 3rd cycle loading.

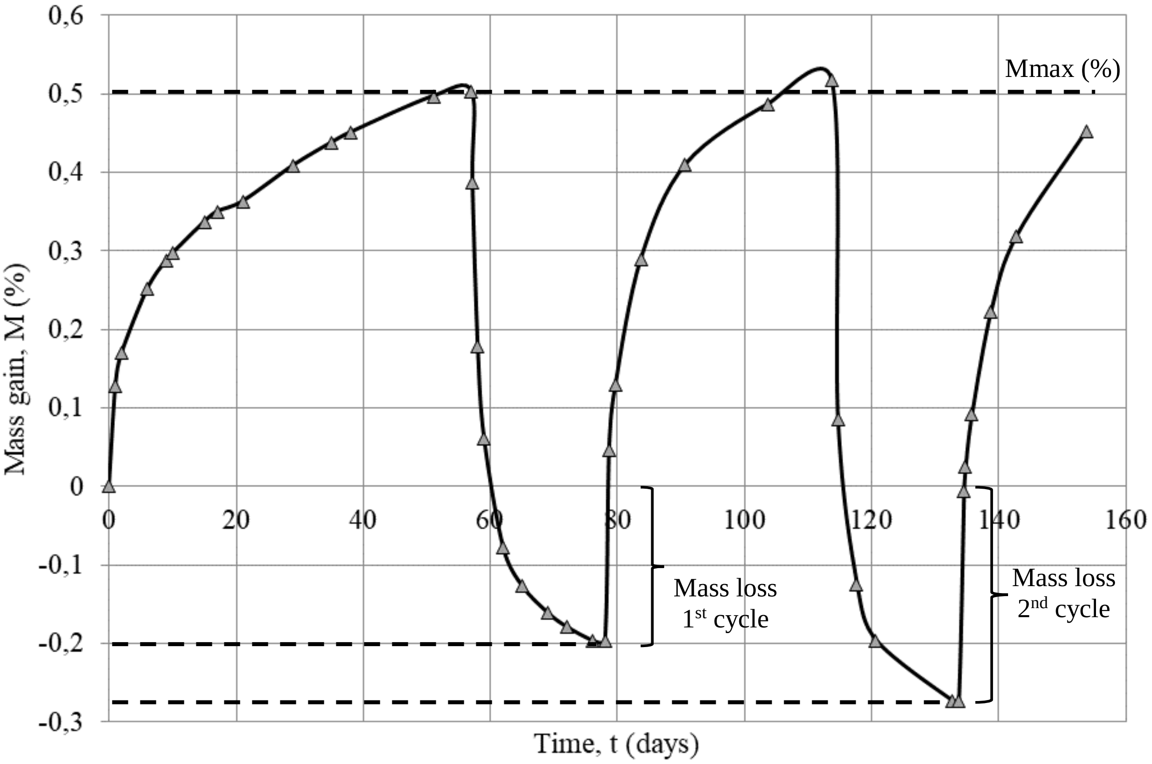

Figure 3. Moisture absorption and desorption curve for one sample hygrothermally aged at 60°C.

This effect is a result of significant mass loss that takes place during hygrothermal aging and is revealed during the drying phases of the material. Chemical decomposition leads to mass loss which practically allows for leachates to be washed out from the FRP structure. Chemical analysis of the aging medium has proved that leachates stem from the fibre/matrix interface paving the way for fibre/matrix interfacial failure [1, 7]. At the same time, hygrothermal aging along with wet/dry cyclic loading promote matrix cracking. The combination of interfacial failure and matrix-cracking leads to intrinsically more space or 'reservoir' for water molecules to penetrate altering the moisture uptake behavior of the material. Fibre/matrix interface failure, matrix-cracking and increasingly higher amount of moisture penetrating the structure are expected to promote a gradual deterioration of the FRP's structural performance. It could be postulated that decomposition may cease when all the active compounds are totally consumed.

With respect to mechanical performance, Fig. 4 illustrates the 'wet' and 'dry' shear modulus of the studied PFRP after 224 days of hygrothermal aging in comparison with the reference (unaged) dry state. As can be seen, hygrothermal aging induces detrimental effects to the material when tested at its wet state. However, this is not the case for aged samples tested at their dry state. It was revealed that, samples aged at 40°C for 224 days, recover completely (100%) their performance when tested at their dry state.

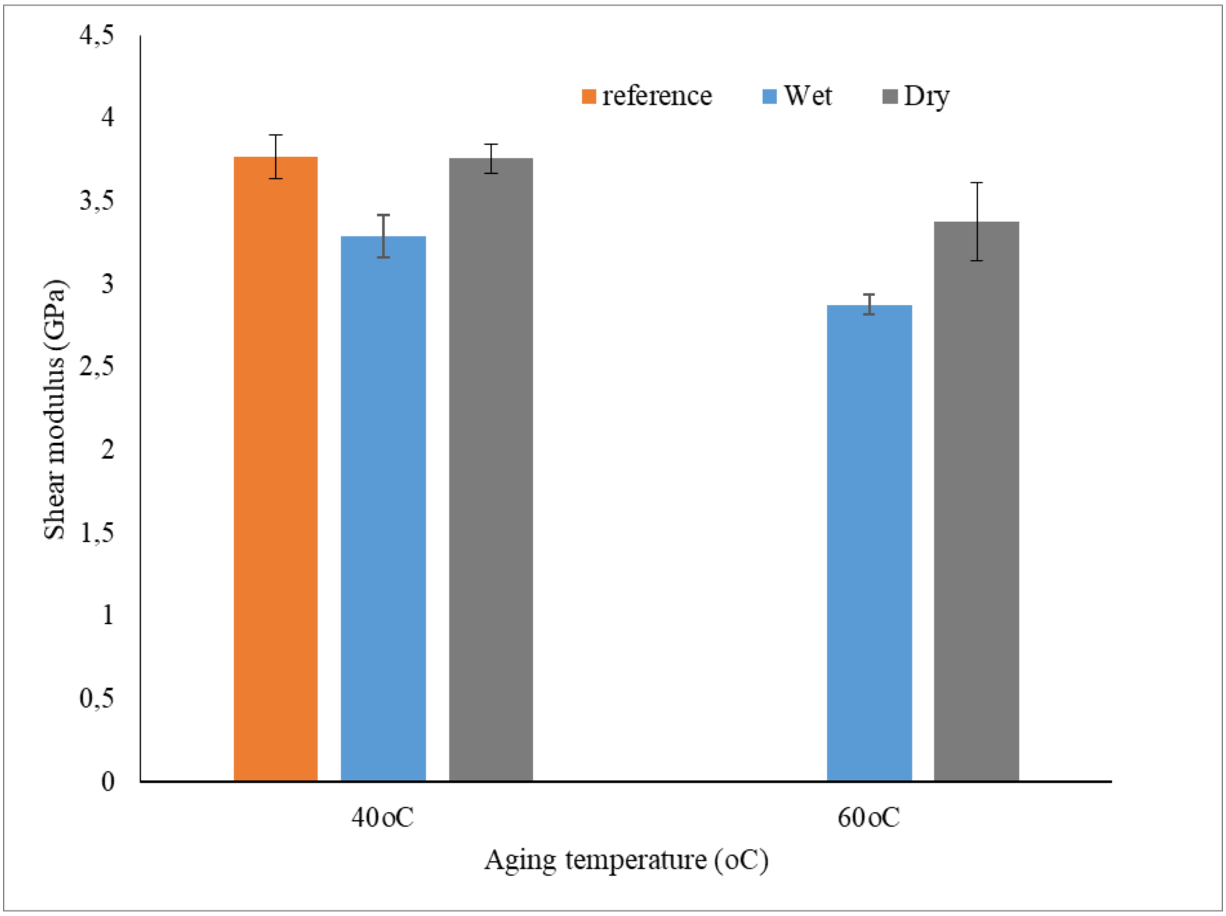

Figure 4. Shear modulus as a function of aging temperature for wet and dry samples after 224 days of aging.

In this respect, it becomes apparent that hygrothermal aging and mass loss due to decomposition become detrimental to the structural performance of PFRPs at their wet state and less significant in the absence of moisture.

3. Conclusions

The effects of wet/dry cycling loading on the moisture uptake behavior of a commercially available pultruded polymer composite were investigated. The cyclic hygrothermal loadings demonstrate that the material losses mass from the initial dry mass due to chemical decomposition, which has an effect on the rate of moisture diffusion. Interestingly enough, the mechanical testing of wet and dry samples revealed that material decomposition is to a certain extent reversible when the material returns to its initial dry state.

Acknowledgments

The EPSRC project DURACOMP (Providing Confidence in Durable Composites, EP/K026925/1) is greatly acknowledged for financial support.

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