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Influence of hydrothermal ageing on the compressive behaviour of glass fibre/epoxy composite pipes

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ABSTRACT

The effects of hydrothermal ageing on the crushing behaviour of glass fibre-reinforced epoxy (GRE) pipes are discussed. Pipes with three different winding angles (±45°, ±55°, ±63°) were manufactured by filament winding process. The pipes were then hydrothermally aged in tap water at a constant temperature of 80 °C for periods of 500, 1000, and 1500 h. Uniaxial compressive tests were conducted on the virgin and aged samples using a universal testing machine in accordance with ASTM D695-10. The tests were also performed at temperatures ranging from room temperature (RT) at 25 °C to 45 °C and 65 °C to study the response of the pipes at elevated temperatures. Scanning electron microscopy (SEM) images were captured and the relationship between the ageing period and strength of the GRE pipes was determined. The results indicate that the strength of the GRE pipes significantly decreases with increase in the temperature and ageing period. On the contrary, the strength increases as the winding angles decrease. The compressive strength of the pipes was also predicted using a Berbinau's based model and was found to correlate well with the earlier obtained experimental results yielding a maximum variation of less than ~25%.

1. Introduction

Recently, glass fibre-reinforced epoxy (GRE) composite pipes have been extensively used in oil and gas industries for the underground transportation of fluid material, such as highly corrosive liquids, oil, water, and natural gas. GRE composite pipes are considered a cheaper alternative to steel pipes because they exhibit fewer problems due to corrosion. In addition, composite tubes possess high specific strength and stiffness and are fatigue resistant [1,2]. GRE pipes are thin-walled and lightweight, which facilitates their handling and transportation. Composites have been the subject of research in a variety of studies that involve both numerical modelling and experimental observations [3–5].

GRE pipes can be subjected to crushing loads when installed underwater; therefore, the compressive properties of GRE pipes are a critical parameter that should be investigated. These pressures can damage the bonds between the fibres and matrix of the pipes, thus affecting their overall performance. Abdewi et al. [6] investigated the crushing behaviour of woven roving glass fibre/epoxy laminated composite tubes. They concluded that after the initial maximum load is achieved during crushing, the crushing load decreases as a sign of material failure in the plastic deformation region. Subsequently, the crushing load rapidly increases at the final failure stage as a result of obtaining an overall average crushing load bigger than the maximum initial crushing load. Xia et al. [7] conducted a study to predict the overall mechanical behaviour and damage mechanisms of fibre-reinforced polymer laminates consisting of $[0, 90_3, 0]_T$ glass fibre/epoxy laminate.

Kara et al. [8] modelled quasi-static and high strain rate deformation, as well as the failure behaviour, of E-glass/polyester under compressive loading. The compressive stress-strain behaviour and the maximum stress of the composite were determined. Mahdi and Kadi [9] investigated the crushing behaviour of laterally loaded glass fibre/epoxy composite elliptical tubes. Their observations demonstrated that the crushing behaviour of such tubes is significantly affected by their ellipticity ratio.

It has been proven that the mechanical properties of composites are critically influenced by environmental factors, where the fibre-matrix interface becomes highly degraded. This degradation is also known to intensify under elevated temperatures [10–12]. This is

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due to the changes that occur in the matrix, which cause the glass fibre/matrix interface to deteriorate [13,14]. Yao and Ziegman analysed the effect of moisture on GRE specimens using an accelerated test method; the elastic compliance of the specimens increased as their moisture content increased [13]. Krystyna and Laurent [15] investigated the effect of ageing on the low-velocity impact behaviour of woven aramid-glass fibre/epoxy composites. They discovered that the compressive strength of material significantly decreased when it absorbed water. Alessi et al. [16] observed the accelerated ageing of cured epoxy resin/polyethersulphone blends and concluded that water absorption leads to degradation of the specimens and results in a plasticizing effect. Lundgren and Gudmundson [17] suggested that laminates may be affected by chemical changes, such as oxidisation and relaxation due to moisture uptake.

The winding angles of GRE composites have also been of interest for numerous researchers. Numerous studies have shown that winding angles indeed play a significant role in the overall performance of GRE pipes under loading. Mistry [18] investigated GRP pipes with various winding angles under combined external pressure and axial compression. The hoop–to-axial membrane stresses of the pipes were found to affect the optimum winding angle. Abdul-Majid et al. [19] observed how winding angles influenced the biaxial ultimate elastic wall stress (UEWS) of GRE pipes and concluded that the mechanical properties of such pipes are highly affected by their winding angles. Mahdi et al. [20] conducted a study on the energy absorption capability of crushed composite tubes with different fibre orientations and discovered that fibre orientation indeed influences the load capacity and energy absorption. Krishnan et al. [21] experimentally investigated the effects of winding angles on the behaviour of glass/epoxy composite tubes under multiaxial cyclic loading. The results indicated that there was a strong dependence of the winding angles on the stress ratios. There is also much interest regarding the effect of temperature on the performance of GRE pipes. Elevated temperatures could cause the properties of such pipes to change, thus changing their overall mechanical properties.

Padmanabhan [22] studied the time-temperature failure analysis of glass/epoxy composites under compression. The results showed that an increase in temperature decreased the compressive strength. Studies on glass/epoxy composites at low temperatures involving the mechanical behaviour and damage characterization of glass/epoxy have been of interest for researchers [23,24].

Analytical studies on uniaxial compression, in which the compressive strength of composites have been predicted using numerical equations, have also been of great interest to researchers [25]. Such studies use the fibre-kinking model, fibre micro-buckling model, and combined modes that use the fibre micro-buckling model and kinking model. The Berbinau's equation is the most well-known equation used for the micro-buckling model. The equation considers that the material fails because of shear failure, which is caused by the fibre micro-buckling, in which the fibres are misaligned and form a kink band. Another study was conducted to investigate the criteria for fibre micro-buckling failure in a 0° unidirectional composite laminate under compressive loading [26]. They predicted the failure of the unidirectional laminate using the 0°-fibre micro-buckling failure mode. It was concluded that such fibres fail in tension on their concave side, rather than their convex side. Although previous studies have been conducted on the aforementioned subject, the influence of hydrothermal ageing on the compressive strength of GRE pipes has not yet been discussed. In the present study, the effects of hydrothermal ageing, elevated temperatures, and winding angles on the mechanical properties of GRE pipes were observed. Pipes with winding angles of ±45°, ±55°, and ±63° were aged for 500, 1000, and 1500 h in tap water at a constant temperature of 80 °C and subsequently compressed at temperatures ranging from room temperature (RT) at 25 °C to 45 °C, and finally 65 °C. Subsequently, a mathematical model was constructed based on Berbinau's equation to model the compressive behaviour of the pipes which was compared with the obtained experimental results.

2. Materials and methods

2.1. Material

A wet-filament winding process was used to fabricate the GRE pipes. The composite pipes were manufactured with various winding angles of ±45°, ±55°, and ±63° using a computer numerical control (CNC) controlled filament-winding machine. E-glass fibres with a linear density of 1200 tex and diameter of 17 μm, and DER-331 epoxy resin supplied by The Dow Chemical Company, were used to create the fibre-matrix interface (Table 1). To achieve resin impregnation, glass fibres were passed through a bath of epoxy resin mixed with hardener, and the wet fibres were wound around a mandrel, of 100 mm in diameter, at different winding angles of ±45°, ±55°, and ±63°. The resulting pipes had an approximate thickness of 2.5 mm, with an internal diameter of 100 mm and length of 1000 mm. After the resin had dried, the pipes were cured by rotating the mandrel at a constant speed for 2 h, in an oven at a temperature of 160 °C. Finally, the pipes were cooled at RT before they were removed from the mandrel. The weight of the fibre rolls were measured before and after winding and the difference between them was used to determine the volume fraction of the fibre and epoxy. By deducting the total weight of the fibre from the overall weight of the pipes, the weight of the epoxy used could be determined. The volume fraction of the pipe could be determined by verifying the densities and weights of the glass fibres and epoxy resin (Table 2).

2.2. Sample preparation

As stated in ASTM D695-10 [27], to conduct uniaxial compression tests on GRE pipes, the height and diameter of the pipes should be identical. Using the original pipes with a length of 1000 mm, the pipes were marked and cut into smaller pieces, with a length of 100 mm, using a band saw (model UE-712A). Subsequently, the ends of the pipes were smoothed using sandpaper to remove any sharp and rough edges. The dimensions of the test specimens are illustrated in Fig. 1.

2.3. Hydrothermal ageing of GRE pipes

To simulate accelerated ageing, the specimens were labelled and immersed in an insulated tank filled with tap water. A simple customised peripheral interface controller (PIC) microcontroller-based temperature controller, illustrated in Fig. 2 was used to control the temperature throughout the ageing process. Using a heating element, the water was initially heated to a temperature of 80 °C to accelerate the ageing process and the specimens were subsequently aged for periods of 500, 1000, and 1500 h. The procedure implemented during ageing process was adopted as reported by

Table 1
Mechanical properties of E-glass fibre and epoxy resin.

Properties	E-glass fibre	Epoxy resin
Young's modulus (GPa)	73	2.05
Poisson's ratio	0.22	0.35
Shear modulus (GPa)	30	0.76
Density (g/cm^3)	2.6	1.16