EXPERIMENTAL AND NUMERICAL LIFE ESTIMATION METHODOLOGY OF FILAMENT WOUND GLASS / VINYLESTER COMPOSITE PIPES USED IN THE OIL AND GAS INDUSTRY

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Abstract

Using fibre reinforced plastics (FRP) in the Oil & Gas industry has proved a cost effective approach that can extend the service life and reduce maintenance time and cost. Nevertheless, there is currently no method for quantifying the ageing effects on composite structures following long term exposure to liquid media. The main objective of this work was to understand how the ageing factors affect the material properties of a composite and establish both testing and numerical methodologies to predict the service life of a composite pipe. The procedure not only enabled saturation of the material and hence a life prediction study to be conducted, but also allowed monitoring of the progression of ageing through the thickness of the composite pipe. The modeling and evaluation of the ageing factors can be used for defining new 'aged' material properties for every ply of the composite pipe, calculating the stress and strain distribution and finally, defining the service life.

1. Introduction

In the Oil & Gas industry the operating environment for the equipment and especially for steel pipelines can be extremely aggressive, and even corrosion resistant alloys (including highly alloyed stainless steel) can decay. As a result of this the operational cost for the industry is increasing, mainly due to increasing maintenance intervals and associated costs. In addition, the installation costs for metal pipes can be great because these materials are heavier compared to composite pipes. One solution successfully adopted is the use of glass reinforced plastics (GRP), and such pipes have been already installed for hundreds of kilometres. For the Oil & Gas industry, one of the most important benefits of using these materials is their lower vulnerability to harsh environments. Because of the environmentally hostile nature of the chemicals they carry, even GRP equipment needs regular maintenance in order to prevent failure. In many instances a protective layer, i.e. liner, is also used to act as a permeation barrier. This can be nylon, polypropylene, polyvinylidene fluoride (PVDF) or polytetrafluoroethylene (PTFE).

However, after years in service, the effect of exposure to harsh environmental conditions combined with mechanical loads may degrade the material's stiffness and strength, as a result of induced matrix cracks and deterioration of the fibre/matrix interface. Combined with a change in glass transition temperature (T_g) ultimately the material fails to meet its design criteria [1]. Herein, the term 'ageing' denotes changes in physical and chemical properties with respect to unaged properties. There is therefore a need for a better understanding of the evolution of material properties during ageing, in order to predict service life and mechanical properties at any given time [2]. So far, the basic method which the designers use for the design of FRP pipes is based on ISO 14692 [3] that cover the qualification of fittings, joints and pipes for certain applications. The design process that ISO 14692 describes treats the pipe as a homogeneous anisotropic material and not as a true orthotropic composite. This holistic design process does not permit for changes in modulus in each composite ply or the stress and strain redistribution through the thickness according to different mass uptake percentages. As the Oil & Gas industry expands beyond current resources, such as in ultra deep water, ultra deep wells, arctic conditions or highly sour reservoirs, composite materials may become the only economically viable structural material available. But because even GRP is not completely resistant to hostile fluids, a testing and analysis methodology is required to enable prediction of likely service life. This paper presents the progress towards the development of the appropriate methodology for prediction of service life of GRP through knowledge of ageing mechanisms when the equipment is exposed to oil and gas environments, and in particular seawater.

2. Experimental Approach

The main objective of the experimental work was to understand how exposure to Oil & Gas environments affects GRP and to develop a methodology to predict the service life of a GRP pipe. The test procedure not only enables saturation of the material and hence a life prediction study to be conducted, but also enables progression of ageing to be monitored through the thickness of the composite pipe wall, through single side exposure of pipe wall sections.

The material used for this study was common GRP (glass fiber reinforced vinyl-ester). The composite material also had two protective layers, one on the outside and one on the inside surface. The outer surface was covered with a vinyl-ester resin layer (the veil) and the inner surface with a vinyl-ester resin layer (the liner). Their main function is to work as diffusion barriers and to shield the structural part of the pipe from ageing mechanisms. First of all, the value of the diffusion coefficient, *D*, was measured. Specimens of GRP pipes were cut at appropriate dimensions following the ASTM D5229 [4] and immersed, in simulated seawater according to ASTM D1141 [5]. In ideal Fickian behaviour, water absorption increases linearly with the square root of time. The diffusion coefficient can be calculated according to ASTM D5229 using Equation 1.

$$D = \pi \left(\frac{h}{4M_{\mathrm{m}}}\right)^2 \left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}\right)^2 \tag{1}$$

where h is the average specimen thickness; M_{m} is the effective water equilibrium content and $\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}$ is the slope of water absorption plot for the initial linear part of the curve (M_1, M_2 describe the mass change % in two different times t_1 and t_2).

In order to monitor mechanical property levels following more representative service conditions (i.e. exposing the inside of the pipe only), a method for conducting single sided exposures has been developed, whereby a section of pipe is sealed over a small aluminium alloy bath (Figure 1), the top of which is machined to match the inner radius of the pipe section to ensure there is no leakage. This ensures that, with the specimen tightly clamped in place, diffusion only occurs through the thickness of the material, from a single side. Moreover, it is possible to monitor and control the internal pressure.

The progress of ageing was monitored by means of mechanical testing. For this, flexural (ASTM D790) [6], tensile (ASTM D638) [7] and short beam strength (ASTM D2344) [8] specimens were used.

Figure 1. Single side exposure prototype

3. Life estimation methodology

3.1 Method

The method used in this study is considering the degradation of the stiffness and strength of the material with respect to liquid, i.e. seawater, absorption and subsequent ageing. Relationships of the elastic constants with respect to the percentage seawater content and time are derived from experimental data and used as input to evaluate the failure of a composite pipe by considering first ply failure criteria. The method is implemented in five distinguished steps, and is presented in the Figure 2.

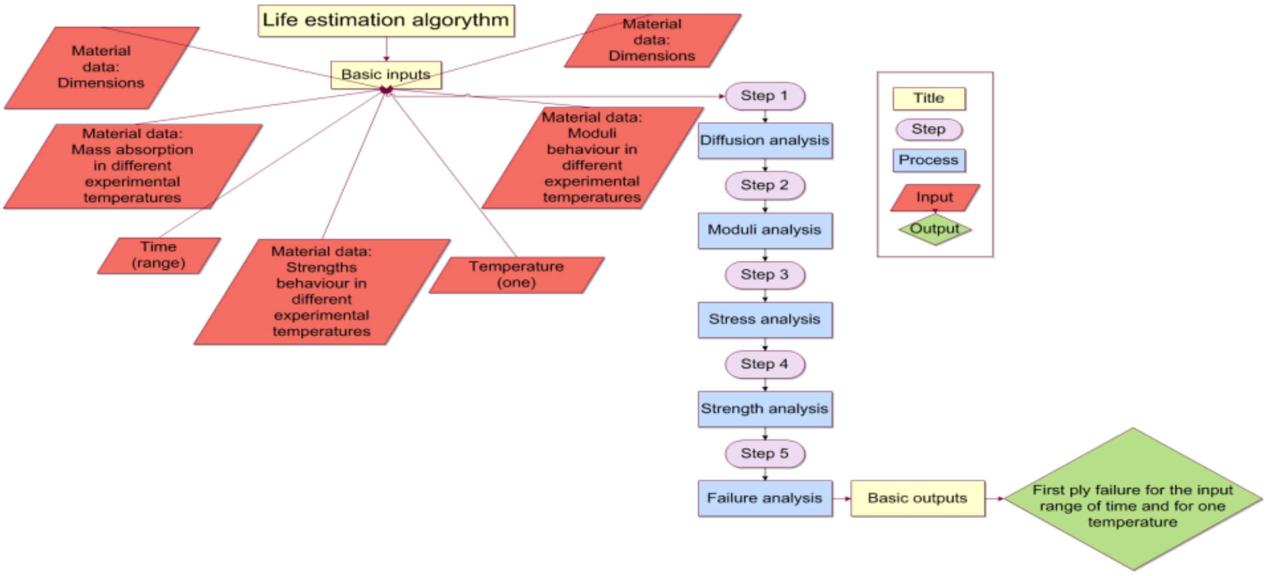
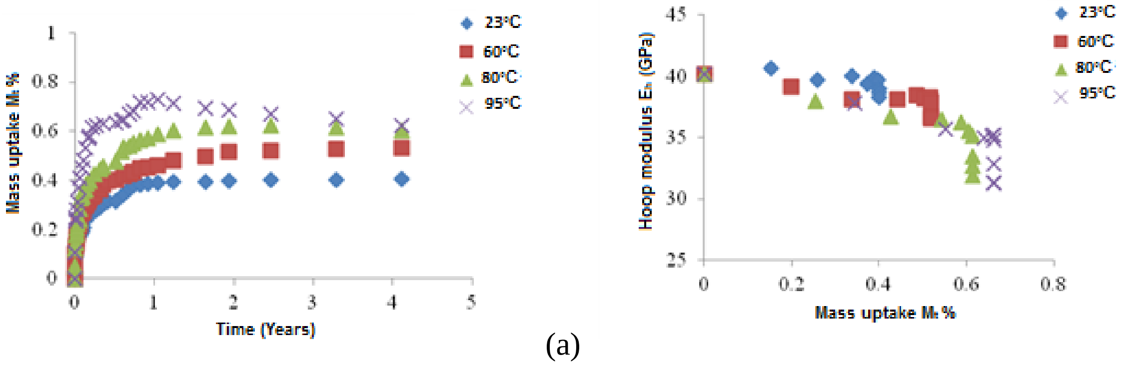


Figure 2. Flow chart of the predictive methodology procedure

3.2 Material and structure

For the purpose of this study, bibliographic data have been used based on the work in [1]. The composite system was a unidirectional E-glass/vinylester composite with a volume fraction of 50-55%. The specimens were manufactured by resin infusion using the Dow Derakane 411-350 vinylester resin. The thickness of the specimens was 2.54 mm and the test specimens were subjected to different environments and immersed in de-ionized water and humidity at different temperatures. The absorption curves versus exposure time for this material and the reduction of elastic modulus in hoop direction E_h versus the percentage of mass increase M_t% are illustrated in Figure 3a and Figure 3b respectively.



(a) (b)

Figure 3. (a) Seawater absorption curves for the material; (b) Variation of hoop modulus with level of seawater absorption [1]

4. Results and Discussion

4.1 Exposure and Mechanical Tests

Specimens from the glass fibre reinforced vinyl-ester pipe were immersed in sea water for more than two months to derive the diffusion coefficient (Figure 4). In order to accelerate the process, three temperatures were chosen to be higher than the service temperature, but at least 20°C lower than the glass transition temperature of the material. Based on previous work [10] there were obvious marks of damage, such as discolouration and cracks both in the inner surface of the specimen (liner) and the outer surface (veil) so the diffusion coefficient couldn’t be calculated accurately. Thus, the test was repeated after removing the protective layers, in order to measure the diffusion coefficient only for the structural part of the material. Following a six months exposure, there weren’t any noticeable cracks on the surfaces; but there was a change in the colour, with exposed specimens becoming darker. However, the plots showing the water absorption were very similar to previous tests with the liner included, and again the leaching had a significant effect on the behaviour of the material. The diffusion coefficient D for the three different temperatures was calculated using Equation 1, before any leaching was observed, and is presented in Table 1. It is evident that there is a relationship between temperature and diffusion coefficient, and whilst the temperature is increasing, the GRP absorbs water faster. Moreover, it was found that without the protective liner layers the diffusion coefficient was higher, so the material absorbs not only more water but at a faster rate.

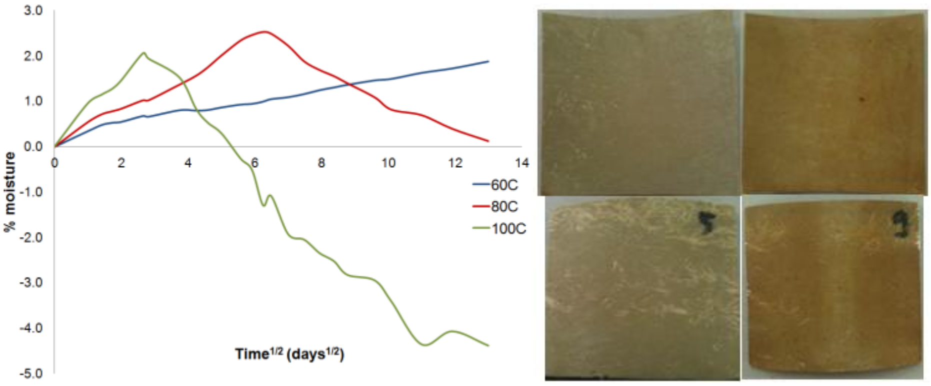


Figure 4. (a) Moisture absorption plot; (b) Specimens for seawater uptake tests
(Note: unaged – left and after exposure at 100°C – right)

Temperature [°C]	***D* [mm^2/s]**
60	9.18×10^{-7}
80	1.29×10^{-6}
100	5.99×10^{-6}

Table 1. Experimentally obtained values for the diffusion coefficient

With respect to the mechanical tests, all results have been normalised using the modulus and strength of the unaged material in order to obtain a better comparison and understanding of the level of material degradation. Firstly, flexural tests were conducted to investigate any change in the flexural behaviour. The flexural modulus presented a drop with exposure time for all temperatures (Figure 5), but after two months exposure the values reach a plateau. This probably is a result of the material having reached a saturation level and any further ageing needs more than 5 months to occur. Regarding the failure modes, these were the same for all specimens and failure occurred initially on the liner spreading afterwards to the structural part.

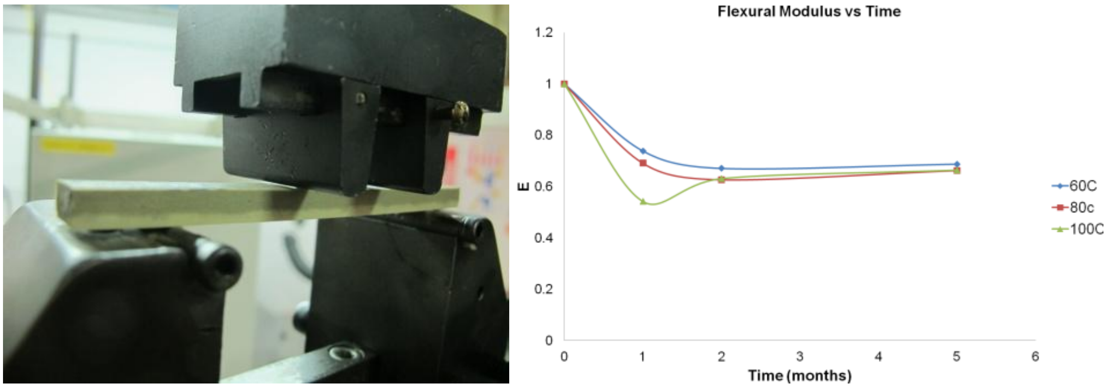


Figure 5. Comparison between ageing regimes – Flexural Tests

The same trend was followed by the tensile test results (Figure 6a) and in particular the modulus of elasticity where an initial reduction was followed by a stable region above two months of exposure. Moreover, it was observed that the higher the exposure temperature, the lower the value; and the higher the degradation. The failure occurred in the middle of the gauge length for all specimens.

Finally, short beam strength tests, presented a reduction of the strength with increasing exposure time and temperature (Figure 6b). Both unaged and aged specimens were found to fail initially on the liner followed by shear failure of the structural part. Moreover, there was no evidence of failure mode change because of ageing.

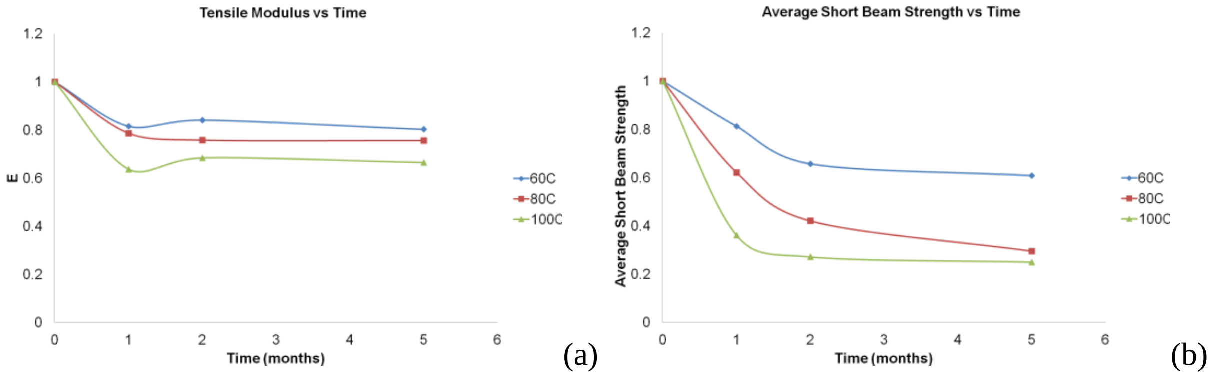


Figure 6. Comparison between ageing regimes (a) Tensile Tests; (b) Short Beam Strength Tests

4.2 Analytical Methodology

The structure in this study is a pipe which is separated into four building block layers of the same material through the thickness and each one has 2.54 mm thickness. For this study, the pipe is assumed to be wound in the hoop direction only (i.e. 90° to the pipe axis). Following the diffusion analysis of the material, the reduction of the elastic constants was expressed as a function of the percentage mass increase. These values were used to calculate the seawater absorption rate, the seawater depth penetration and the moduli reduction of the composite pipe. Figure 7a illustrates the results of mass uptake of the pipe as a function of time for each one of the exposure temperatures considered. At lower temperatures the initial high absorption rate region is extended to longer times compared to higher temperatures. Thus, the time period needed for the GRP pipe to reach the saturation level is higher at lower exposure temperatures. It has been considered that the diffusion in each layer starts when the previous one has reached a saturation stage.

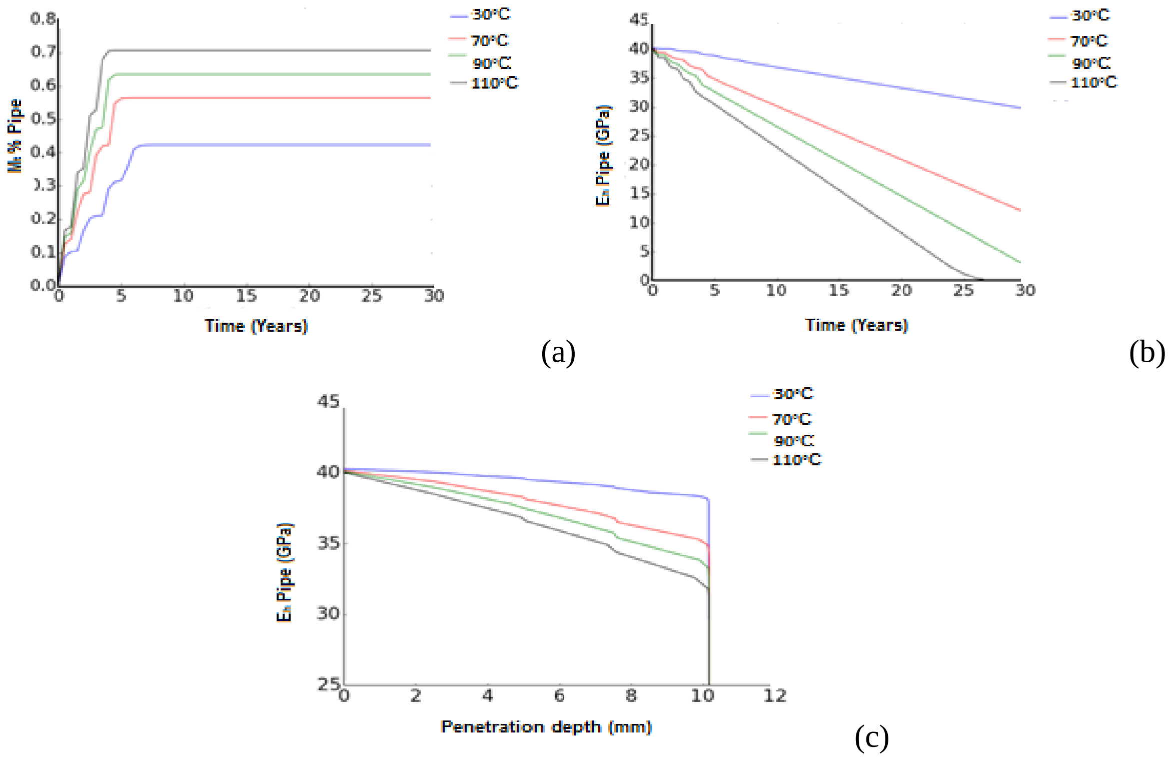
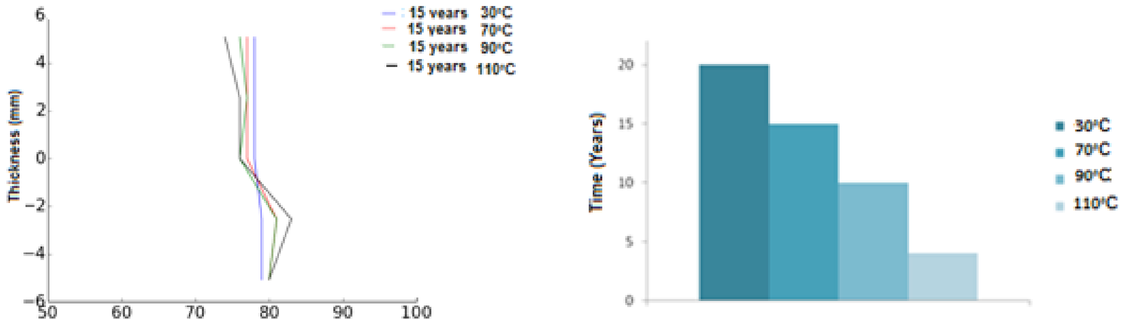


Figure 7. (a) Seawater uptake of the pipe; (b) Calculated variation of pipe hoop modulus with time; (c) Reduction of hoop modulus with penetration depth of the fluid in the pipe wall for different temperatures

Figure 7b shows the hoop modulus of the pipe with respect to the exposure time at different exposure temperatures. The higher the exposure temperature, the higher the degradation of the mechanical properties is. Furthermore, the modulus reduction rate is much higher as the exposure temperature increases. Finally, Figure 7c illustrates the reduction of the hoop modulus of the pipe according to the penetration depth of the fluid for different exposure temperatures. These results are derived from the diffusion analysis that provides the variation of the mass increase with respect to the distance from the exposure surface for the specific cylindrical geometry of the GRP pipe. With increasing temperature the absorption and the fluid penetration depth is increased. Again it has been assumed that the penetration in each layer begins following saturation of the previous layer. The reduction of the hoop modulus is greater as the penetration depth increases since the M_t increases. The rate of this reduction is strongly related to temperature. In the Figure 7c prior to the saturation point, the degradation of the modulus seems to change and be higher from layer to layer in every temperature separately, which is due to the fact that the absorption of fluid that provokes this degradation in every layer is different. One of the advantages of the current methodology is the calculation of the stress distribution through the thickness of the composite pipe. For a given temperature, the stress distribution is dependent on the reduction of the stiffness, i.e. elastic constants, of every layer of the pipe with the exposure time. Figure 8a presents the stress distribution for different temperatures following a hypothetical exposure time of 15 years. With the increase of temperature there is divergence of stress distribution which is expected to have a significant influence on the life of the composite pipe.



(a) (b)

Figure 8. (a) Stress distribution through the thickness for various exposure temperatures; (b) Predicted life of the composite pipe using Tsai – Hill failure criteria

The last step of the predictive methodology has been performed using Tsai-Hill failure criterion that consider the ply as a homogeneous material and calculate the failure of the first ply in the laminate. This failure criterion cannot distinguish between different failure modes including fiber failure, matrix failure, and fiber-matrix interface failure. Figure 8b presents the time (year) to failure for the pipe exposed to seawater at different temperatures as this is calculated by applying Tsai-Hill failure criteria that take into account the tensile strength of the laminate in two directions as well as the shear strength of the laminate. With increasing service temperature the estimated life of the pipe reduces by approximately 8% every 10°C.

5. Conclusions

GRP pipes are installed for hundreds of kilometres over hostile terrains because of their improved performance over steel in corrosive environments. However, failure can still occur through diffusion of the liquid through the pipe wall causing material degradation and eventually leading to catastrophic burst failure of the pipe. The research reported herein marks initial development of a test methodology for understanding appropriate ageing mechanisms and how they affect the composite material through the thickness. It focuses on seawater exposure and subsequent ageing. It has been shown that, by measuring the mechanical properties of the material, both flexural and tensile modulus could be predicted for a certain time. Results included observation of leaching effects; which have been seen to have significant effect on mass uptake measurements and hence quantifying the diffusion process for the material. Rationale has been proposed for exposing small parts of material from a single side only, avoiding having big parts of pipes, which demand time and space for installation. Concerning the analytical solution, this is based on the calculation of stress distribution and first ply failure at different temperatures. The seawater absorption and consequently the fluid penetration were calculated and were found to increase with increasing temperature. The calculated stresses and the reduced strengths due to ageing are implemented in the failure criteria in order to predict the time that first ply failure will occur, information which is important for the design process.

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