

A STEP FORWARD IN CHARACTERIZING THE PERFORMANCE OF GFRP RODS IN CONCRETE

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ABSTRACT

One significant challenge facing the world today is the decay of infrastructure. A major component of infrastructure decay is the degradation of bridges and highways due to corrosion of the embedded reinforcing steel. This problem has prompted the development of a variety of alternative strategies for increasing the service life of reinforced concrete structures exposed to harsh environments. Over the last two decades, many advanced metallic and non-metallic materials have been developed for withstanding severe corrosion typically encountered in concrete bridge decks. Glass Fibre Reinforced Polymer (GFRP) materials have not been used in large-scale construction applications despite their numerous advantages over traditional materials such as steel. Economic and technical barriers hinder industry's adoption of this new technology. The primary economic barrier preventing their use is often their high initial cost whereas the primary technical hurdle remains the relative uncertainty about the effect of these new materials on the long-term performance of FRP reinforced structures in their service environment. Based on a combination of first principle physical-chemical modelling procedures and accelerated testing, a novel approach is proposed for assessing the long-term performance of GFRP rods in concrete. Preliminary results show good agreement with observed laboratory and field performances.

1. INTRODUCTION

The cost of protecting and restoring concrete structures worldwide is a large and growing problem (>\$100 billion/yr). A major component of infrastructure decay is the degradation of bridges and highways due to corrosion of the embedded reinforcing steel. The main long-term deterioration mechanism involves moisture movement and the transport of dissolved harmful chemical species within concrete. In particular the ingress of chlorides is a major cause of early deterioration of reinforced concrete structures due to subsequent corrosion. Highway bridges and parking garages exposed to de-icing salts are among structures that are most affected by corrosion-induced damage. This problem has prompted the development of a variety of alternative strategies for increasing the service life of reinforced concrete structures exposed to harsh environments. Among the most promising materials that have been developed for withstanding severe corrosion typically encountered in concrete bridge decks are Fibre Reinforced Polymer (FRP) materials. However, despite their numerous advantages over traditional materials such as steel, adoption of these materials by industry has fallen far short of initial expectations. Economic and technical barriers hinder industry's adoption of this new technology. The

primary economic barrier preventing the use of performance composites is often their high initial cost whereas the primary technical hurdle remains the relative uncertainty about the long-term performance of FRP reinforced structures in their service environment. Current practice is that up-front costs control the choice of materials and design alternatives without consideration of how cost effective a material might be over the life cycle of the structure. Clearly, this practice has failed to provide reliable long-term performance of structures exposed to aggressive environments at low costs.

To overcome this cost-based barrier to the adoption of new technology, such as FRP the construction industry needs practical economic methods, such as life cycle cost analysis, for evaluating alternative construction materials in a comprehensive and consistent manner [1]. To conduct a credible life cycle cost analysis, one needs rational tools to predict the performance of the alternative designs (structures and materials) in their natural environment. The objective of this research was to obtain insight into the service life of composite rods in real life conditions. To simulate real life conditions, rods were exposed for almost 1000 hours to neutral water and sodium hydroxide solution (pH 14) at several temperatures, with a maximum of 70 degrees Celsius [2],[3]. Figure 1 shows the condition of a GFRP rod at the end of the exposure period under 70 degrees Celsius. If the rod would be embedded in concrete this accelerated test environment would represent 25 years of exposure in a Northern climate [4].



Fig. 1: GFRP composite containing 26 wt% polymer and 74 wt% glass after 1000 hrs of exposure under 70 degrees Celsius.

2. MATERIALS AND METHODS

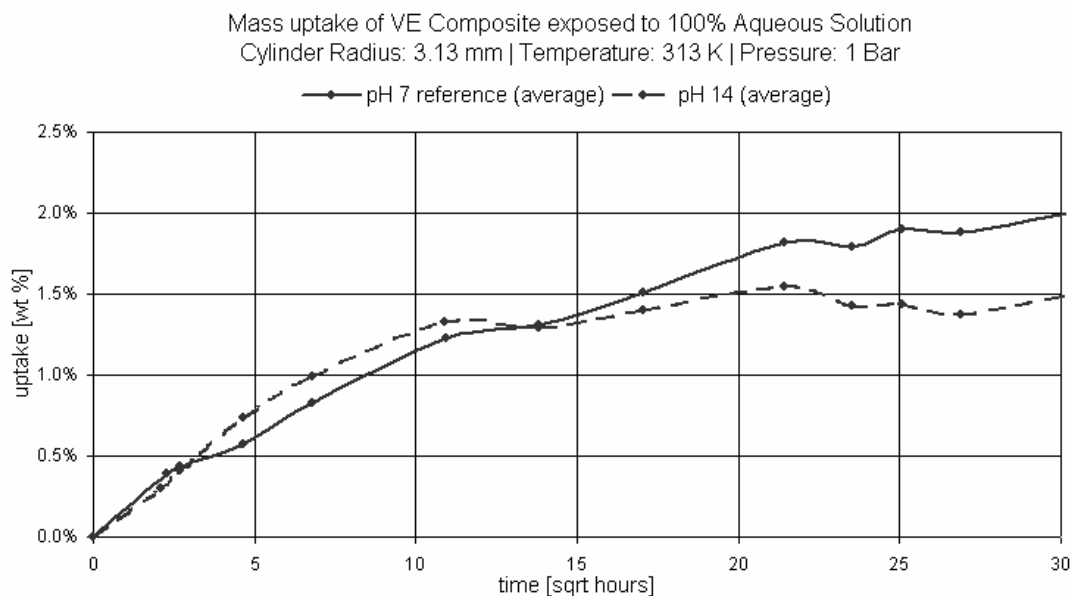
GFRP samples were exposed to 100% demineralised water (pH 7) and to an alkaline (sodium hydroxide) solution with pH 14. Firstly, samples were dried in a vacuum oven for one month at 50 degrees Celsius. Secondly, uptake measurements were carried out at two temperatures: 40 and 70 degrees Celsius. Five samples were measured in each of the four conditions. Once measurements were finished, samples were immediately dried in a vacuum oven at 50 degrees Celsius. Drying measurements were completed about two weeks later once equilibrium was reached.

In order to assess the effect of the considered environments on the mechanical properties of the GFRP rod, a Dynamical Mechanical Analysis was carried out for estimating the storage modulus of the exposed samples. Properties of the rod were determined by applying an oscillating force at 1 Hertz and 25 degrees Celsius, and measuring the material's response.

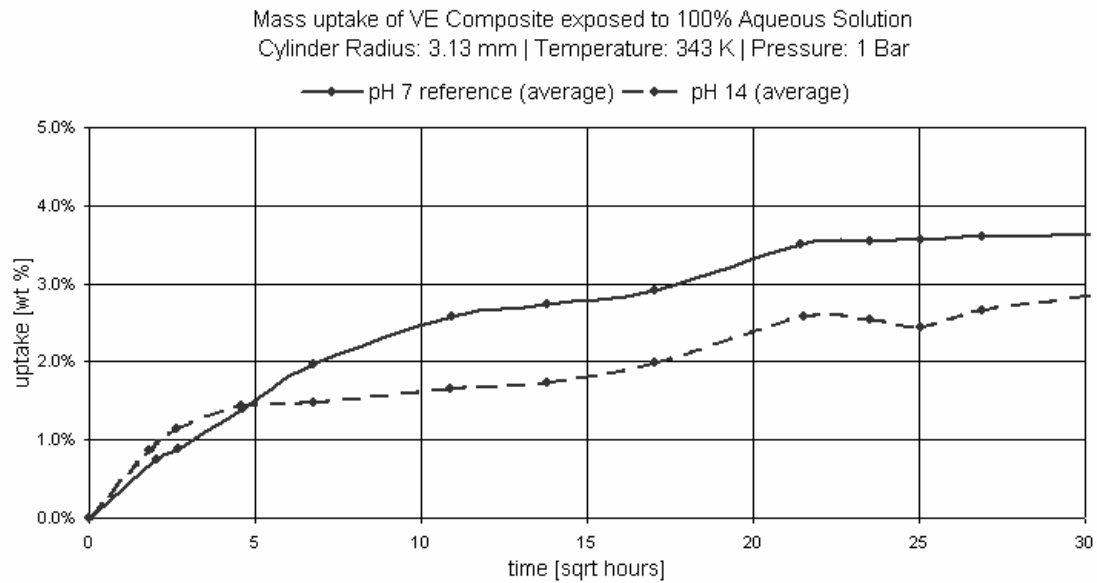
3. RESULTS AND DISCUSSIONS

3.1 Diffusion and Chemical Resistance Properties

The results of the uptake measurements are depicted in Figure 2. During exposure at pH 14, the composites lost on average 0.7 weight percent of mass. Although the rate of loss varied with exposure temperature, the total equilibrium loss was equal.



a)



b)

Fig. 2: Weight uptake at a) 40 degrees Celsius and b) at 70 degrees Celsius.

It appeared that the mass loss could be attributed to the corrosion of the helical glass fibre on the surface of the composite. As such, the measurements allowed us to determine the glass corrosion rate. In case of solutions with high alkalinity, the corrosion rate is 5×10^{-13} m/s at 40 degrees Celsius and approximately 1×10^{-11} m/s at 70 degrees Celsius.

On basis of the observations described above and the absorption profiles at different temperatures and alkalinity, we could conclude that the vinyl ester resin was chemically resistant to sodium hydroxide. Hence, the absorption was not “disturbed” by simultaneous loss of weight by vinyl ester chains that are “cut” and solve in the aqueous solution.

So, the uptake process was controlled by diffusion of water and possibly sodium hydroxide [5]. Although uptake was governed by a slightly anomalous diffusion process, there was no significant difference - after compensation for the corrosion of the helical glass fibre by sodium hydroxide - between uptake of neutral and alkaline solution.

While the activity of sodium hydroxide in water is rather low, around 0.02 even at pH 14, the thermodynamical drive for mass transfer into the composite is low. Moreover, the sodium hydroxide diffuses as one “specie” because of electroneutrality. The resulting diffusion rate follows from the average size of the two ions: Na^+ and OH^- . Of course this average size is larger than water. Because the diffusion rate of molecules in vinyl ester resins - far below their glass transition temperature - strongly reduces as function of molecular size, the resulting diffusion rate of sodium hydroxide is much lower than water. Water has a diffusion coefficient of around 1×10^{-12} m^2/s in ambient conditions; the diffusion rate of sodium hydroxide would then be in the order of 1×10^{-14} m^2/s . Taking the small thermodynamical drive and the low diffusion rate into account, one

must realize that the flux of sodium hydroxide into the composite will be around a factor 1000 lower than water [6], [7].

Hence, one may argue that the outside vinyl ester resin can serve as a membrane for the outside sodium hydroxide. This is important while we previously showed that internal glass fibres are quite susceptible to corrosion by sodium hydroxide. If the outside vinyl ester resin would stay in shape during lifetime, the membrane function is very important in establishing a long service life!

3.2 More on the Boundary Layer

For the outside vinyl ester resin to stay in shape, the two conditions described below are of major importance.

1. The layer must be tight and have a sufficient thickness (see Figure 3). From SEM images of samples we could observe a minimum thickness of 50 micrometer. This is the absolute minimum while we also have to account for unforeseen impact during transport and real life application.

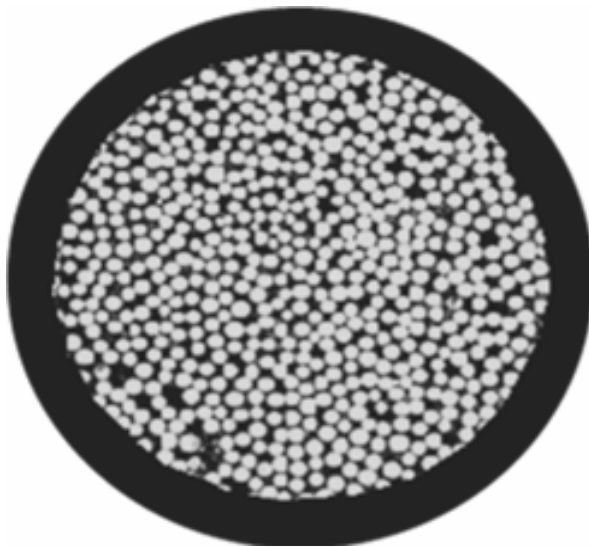


Fig. 3: Schematic impression of the cross section of a composite rod with a boundary layer of vinyl ester resin (in black) with a sufficient thickness.

2. Water diffuses through the boundary layer with a significant rate. If water would react with a fibre or an adhesive (the binding between glass fibre and resin must be facilitated by an adhesive called “sizing”; see figure 4 for an example of a coated fibre), this could result in a volume change and a subsequent change in shape of the outer vinyl ester resin. The sizing applied in the rod composites evaluated have of course a good resistance to water; worded differently: a low susceptibility to hydrolysis by water. It is expected that if the glass fibre is completely wetted by sizing, the required amount of water available for chemical reaction is very limited.

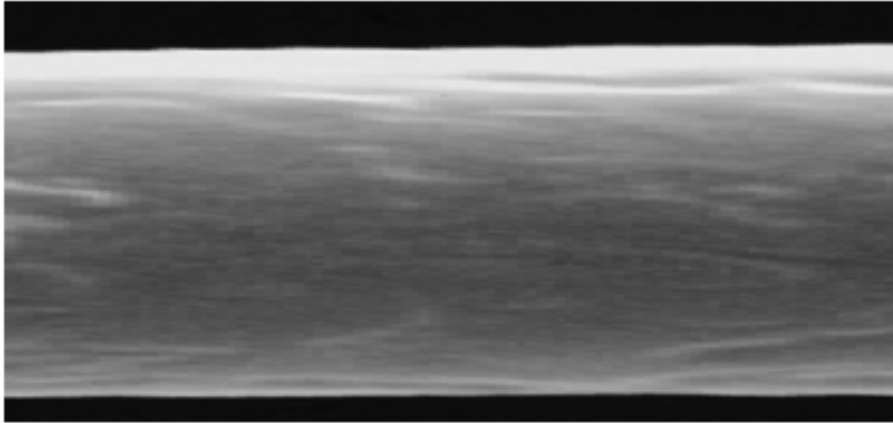


Fig. 4: Detailed view on glass fibre and the surface which is coated with 1.5 to 3 wt% of sizing.

However, wetting may be suboptimal. Hence, small cavities in which liquid water could accumulate may be present. It was interesting to evaluate how much time it would take for water to reach a critical concentration for chemical reaction with sizing in such a cavity. Subsequently we evaluated whether, after a chemical reaction is initiated, this could give rise to an additional drive for diffusion: osmotic pressure. If osmotic pressure caused by water with reaction product, would come into a play a blister on top of the glass fibre might be formed. Such a blister would certainly be able to alter the dimensions of the boundary layer.

It was shown that water reaches relatively fast the critical concentration in a cavity just below the outside vinyl ester resin layer (diffusion path approximately 50 micrometer from the outside). As such, theoretically, reaction with sizing could find place. Then, for subsequent blister formation driven by osmotic pressure, the reaction kinetics is of importance.

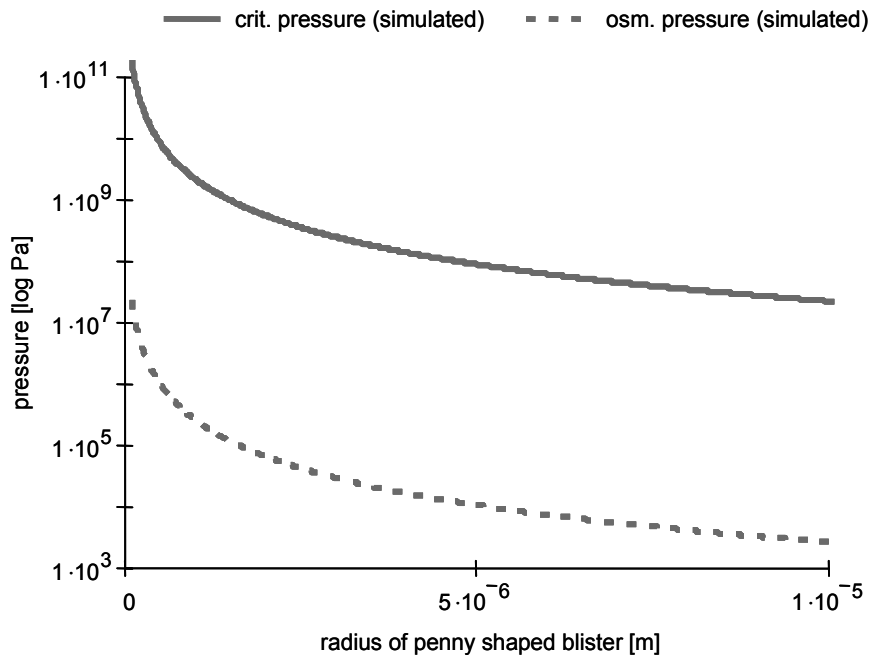


Fig. 5: Pressures in case of a sizing decomposition equilibrium constant of 0.8.

It was shown that, even if decomposition reaction equilibrium would lie far to the right, the energy that is required for blister expansion in this sort of composite is much too high to allow blister growth initiated by water in such a cavity! [8]. Figure 5 clearly shows that the osmotic pressure that could develop at the fibre-matrix interphase is much smaller than the critical pressure needed to allow blister growth. Hence, it is expected that no growth of any blister takes place. As a consequence, the volumetric change of the composite, due to blister growth, is zero.

3.3 Dynamical Mechanical Analysis

Further investigations to evaluate the effect of chemical reaction with sizing, was carried out by use of dynamical mechanical analysis. By measuring the dynamical mechanical properties of the non-aged material, a baseline was established for the study of ageing effects. Measurements were carried out after drying of the aged samples, at a frequency of 1 Hz and 1 temperature of 25 degrees Celsius. Fit for purpose samples were obtained from the original rod (see Figure 6).

The dynamical force is applied perpendicular to the fibre direction. It appeared that the storage modulus of the aged material at 70 degrees Celsius, independently of being exposed to neutral or alkaline solution, was 2 GPa lower (25 GPa instead of 27 GPa). The loss modulus was in all situations equal: around 1 GPa. The fact that the aged composite has a lower storage modulus is the indication that the strength of the interface between glass and resin is slightly reduced.



Fig. 6: Sample for DMA analysis.

4. CONCLUSION

The findings from dynamical mechanical analysis are in line with the other experimental observations and forthcoming calculations. According to this research, rods with a sufficient outside boundary layer, containing glass sizing with a low susceptibility to water hydrolysis and the right kind of vinyl ester resin which is properly processed, shows strength retention of 92% after 25 years of exposure. In compliance with the kinetics described in this report, this would give strength retention of around 70% after 100 years. To validate these findings more thoroughly, it is advised to carry out some additional uptake and subsequent DMA experiments on composites with different thicknesses of the boundary layer. With this regard one could also think of testing a micro composite. This composite could consist of one glass fibre coated with a representative amount of sizing with on top a layer of vinyl ester resin.

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