DEGRADATION OF GLASS FIBRE REINFORCED POLYMER (GFRP) COMPOSITE SUBJECTED TO DIFFERENT ENVIRONMENTAL CONDITIONS

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Polimer bertetulang gentian kaca (*GFRPs*) ialah bahan komposit yang terdiri daripada gentian pengukuh kaca yang tertanam dalam matriks polimer/plastik seperti epoksi, ester vinil, atau resin poliester. Matriks mengikat gentian kaca bersama-sama, menyediakan perlindungan permukaan, dan bertindak sebagai medium pemindahan beban antara unsur gentian manakala unsur gentian bertindak sebagai komponen galas beban utama. Kemerosotan *GFRP* dalam aplikasi luar menjadi kebimbangan bagi ramai jurutera dan pakar. Kebimbangan ini menjadi lebih kritikal apabila *GFRP* dilaksanakan untuk membaiki struktur sensitif seperti saluran paip minyak dan gas serta struktur marin. Struktur sedemikian boleh didapati dalam keadaan persekitaran perkhidmatan yang teruk. Beberapa kajian telah menyiasat kemerosotan komposit *FRP* atau *GFRP* dalam keadaan simulasi yang mungkin tidak mencerminkan sepenuhnya keadaan sebenar, manakala hanya kajian yang terhad telah mempertimbangkan kesan keadaan cuaca sebenar di beberapa negara. Proses degradasi di bawah keadaan sebenar di negara-negara ini sedikit sebanyak akan sah di lokasi geografi masing-masing yang mungkin tidak terpakai untuk lokasi dan keadaan lain di seluruh dunia. Malaysia adalah sebuah negara tropika dengan keadaan persekitaran yang unik (hujan lebat, suhu tinggi, kelembapan tinggi). Oleh itu, sifat mekanikal *GFRP* di lokasi ini mungkin mengalami degradasi khusus yang berbeza daripada keadaan lokasi lain di negara lain. Oleh itu, kajian ini bertujuan untuk menentukan kesan jangka panjang keadaan penuaan semulajadi di semenanjung Malaysia terhadap kemerosotan sifat mekanikal aplikasi *GFRPs* di bawah tiga keadaan persekitaran iaitu atmosfera, bawah air dan bawah tanah. Ia juga bertujuan untuk mengkaji morfologi spesimen selepas pendedahan kepada tiga persekitaran yang dinyatakan di atas. Sampel *GFRP* disediakan menggunakan teknik fabrikasi *hand-layup* daripada empat lapisan tikar gentian kaca E tenunan dua arah 0°/90° dan resin epoksi serta pengeras (agen pengawet). Sampel yang disediakan telah didedahkan dalam tiga keadaan lapangan yang dinyatakan di atas untuk empat tempoh pendedahan yang berbeza iaitu satu, empat, enam dan sembilan bulan. Ujian tegangan digunakan untuk menilai kelakuan degradasi *GFRP* dalam tiga persekitaran tersebut. Penemuan mendedahkan bahawa persekitaran atmosfera kurang mempengaruhi kapasiti kekuatan *GFRP* manakala persekitaran bawah tanah dan bawah air menyebabkan pengurangan ketara dalam kekuatan tegangan dalam tempoh sembilan bulan pendedahan. Sebanyak 18%, 64% dan 63% pengurangan kekuatan tegangan telah direkodkan untuk sampel terdedah kepada persekiran atmosfera, bawah tanah dan bawan air. Tambahan pula, kegagalan sampel dalam persekitaran atmosfera menunjukkan kegagalan separa dalam matriks dan gentian, manakala sampel bawah tanah dan bawah air menunjukkan potongan bersih pada sisi matriks dan gentian. Keputusan mikroskopi elektron pengimbasan *(SEM)* untuk sample terdedah kepada persekitaran atmosfera menunjukkan keretakan yang tidak teratur berbanding dengan persekitaran lain. Keputusan *SEM* sembilan bulan untuk pendedahan persekitaran bawah tanah dan bawah air menunjukkan bahawa kegagalan gentian dan matriks dicirikan oleh kegagalan potongan-bersih. Tambahan pula, dengan hanya sembilan bulan, trend degradasi dapat dilihat dengan jelas dengan ketepatan yang sangat tinggi di mana R^2 melebihi 0.96. Secara keseluruhannya, kajian ini mempunyai impak yang signifikan dalam memahami tingkah laku degradasi jangka panjang komposit *GFRP* dalam persekitaran di kawasan tropika Malaysia. Selanjutnya, ia akan meningkatkan keyakinan dalam penggunaan komposit *GFRP* dalam membaiki dan membetulkan struktur sensitif.

ABSTRACT

Glass fibre-reinforced polymers (GFRPs) are composite materials that consist of glass reinforcing fibres embedded in polymer/plastic matrix such as epoxy, vinyl ester, or polyester resins. The matrix binds the glass fibres together, providing surface protection, and acting as a load transferring medium between the fibre elements while the fibre elements act as the main load-bearing component. The degradation of the GFRP in outdoor applications becomes a concern for many engineers and specialists. This concern becomes more critical when GFRPs are implemented to repair sensitive structures such as oil and gas pipelines and marine structures. Such structures can be found in harsh service environmental conditions. Several studies have investigated the degradation of FRP or GFRP composites in simulated conditions which might not fully reflect the real conditions while only limited studies have considered the impact of the actual weather conditions in a few countries. The degradation process under the actual conditions in these countries would be to some extent valid in their respective geographical location which might not be applicable to the other locations and conditions around the world. Malaysia is a tropical country with unique environmental conditions (heavy rain, high temperature, high humidity). Hence, the mechanical properties of GFRPs in these locations might be undergone specific degradations that are different from other location conditions in other countries. Therefore, this study aimed at determining the long-term impact of the natural ageing conditions in peninsular Malaysia on the mechanical property's degradation of GFRPs applications under three main environmental conditions which are atmospheric, underwater, and underground. It also aimed at examining the morphology of the specimens after the exposure to the above mentioned three field conditions. The GFRP samples were prepared using hand-layup fabrication technique from four layers of 0 °/90 °bi-directional woven E-glass fibre mats and epoxy resin and hardener (curing agent). The prepared samples were exposed in abovementioned three field conditions for four different exposure durations which are one, four, six, and nine months. Tensile test was used to evaluate the degradation behaviour of the GFRPs in the three environments. The findings revealed that the atmospheric environment has less influence on the GFRP strength capacity while underground and underwater environments cause a significant reduction in the tensile strength over the nine months of exposure. A total of 18%, 64% and 63% reduction in tensile strength was recorded for samples exposed to atmospheric, underground and underwater environments. Furthermore, the failure of the samples in the atmospheric environment shows partial failure in the matrix and fibres, while the underground and underwater show a lateral clean cut of the matrix and fibre. Scanning electron microscopy (SEM) results in the atmospheric environment exposure exhibited irregular fracture compared to the other environments. The nine-month SEM results for the underground and underwater environment exposure show that the failure of fibres and matrix was characterized by clean-cut failure. Furthermore, with only nine months, the trend of degradation is seen clearly with very high accuracy where the R^2 more than 0.96. Overall, this study has a significant impact on understanding the long-term degradation behaviour of the GFRP composites in environments in Malaysia's tropical region. Further, it will increase confidence in implementing the GFRP composites in repairing and rectifying sensitive structures.

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LIST OF SYMBOLS

A_c	The cross-sectional area of the composite element
A_f	The cross-sectional area of fibre element
A_m	The cross-sectional area of the matrix
F_c	Total composite force
F_m	Matrix force
F_f	Fibre force
σ_c	average tensile strength in the composite
σ_m	Matrix tensile strength
σ_f	Fiber tensile strength
V_m	The volume fraction of the matrix
V_f	The volume fraction of fibres
E_{cl}	longitudinal modulus of elasticity of the composite
E_{ct}	Transverse modulus of elasticity of the composite
E_m	Modulus of elasticity of the matrix
E_f	Modulus of elasticity of the fibres
ε_m	Matrix strain
ε_f	Fibre strain
ε_{ct}	The transverse strain of composite
Δ_c	total deformation of the composite
Δ_m	Deformation of matrix
Δ_f	Deformation of fibres
γ_{12c}	Shear strain of the composite
τ_{12c}	Shear stress of the composite
G_{12c}	Shear Modulus of the composite
T_{cr}	Critical softening temperature
T_{m}	Melting stage temperature
P_{R}	Residual value
T_g	Transition temperature

LIST OF ABBREVIATIONS

FRPs	Fibre-reinforced polymers
FRP	Fibre-reinforced polymer
GFRP	Glass fibre reinforced polymer
ASTM	American Society for Testing and Materials
AAB	Angled failure at the bottom grip /tab area
AAT	Angled failure at the top grip /tab area
DGM	Delamination failure at the middle gauge area
GAB	Grip/tab failure at the bottom grip /tab area
LAB	Lateral failure at the bottom grip /tab area
LAT	Lateral failure at the top grip /tab area
LGM	Lateral failure at the middle gauge area
M (AS) AB	Multi-mode failure at the bottom grip /tab area
M (GS) AT	Multi-mode failure at the top grip /tab area
SGM	Splitting failure at the middle gauge area
XGM	Explosive failure at the middle gauge area
XGT	Explosive failure at the top gauge area
SEM	Scanning Electron Microscope

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