

EFFECTS OF TROPICAL WEATHER ON THE COMPRESSION PROPERTIES OF PULTRUDED GFRP COMPOSITES

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ABSTRACT: Glass fibre reinforced polymer (GFRP) is a composite material, which consists of polyester thermosetting resin as matrix and glass fibres as reinforcement. Pultruded GFRP is mainly used as structural sections and as structural rehabilitation and repair material. It was observed that the current required technical and design data of pultruded GFRP sections is rather limited especially with regard to material properties and its performance in the tropical climate. This study was conducted experimentally to investigate the compression properties of pultruded GFRP under tropical climate. Special observations on the effects of the fibre orientations and stacking sequences in laminates were made. There were six different fibre orientations of GFRP plates of 6.35 mm nominal thickness with different stacking sequence selected for the test samples. The plates were fabricated by local manufacturer according to the commercial quality requirements. A total of 432 GFRP samples were tested for physical and compression properties. Measurements were taken at 3, 6, 12 and 24 months period of exposure to tropical weather. The statistical test data were analysed using Weibull distribution. The test results showed that the properties of GFRP material were significantly affected due to the environmental agents. In general, surface degradation was significant after 12 months exposure. Surface roughness and discoloration on the top surface of the samples were also observed with the bottom surface not affected by the exposure at all. The effect on compression properties of the exposed GFRP samples was also significant, but varied with fibre quantity. Ultimately, the compression properties with respect to the period of exposure under tropical weather was formulated and proposed for design.

Keywords – Pultruded Glass Fibre Reinforced Polymer Composites, Compression, Tropical Weather, Environmental Agents, Weathering Coefficient.

1. INTRODUCTION

Since 1990s, the use of the glass fibre reinforced polymeric composites in the construction industry has grown very rapidly especially in developed countries. The applications of the composite material are mainly in building structures, bridges, offshore structures, etc. However, the development of the material in the construction industry in Malaysia is still at its infancy. Pultruded GFRP is categorised as a high-performance composite material due to its ability to sustain structural loading. In addition, it has the advantages of high strength-weight ratio, dimensional stability, and with the right selection of resin formulation, will give good weathering properties, chemical resistance, electrical properties, fire and heat resistance.

Due to the rapid development of fibre systems in continuous forms, the desired property data of pultruded GFRP sections must be concurrently developed. In present applications of GFRP, the use of gel coat as a finished layer on the hand-laid up products have been applied successfully to improve the durability of the materials. But for pultruded GFRP sections, the employment of gel coat as a finished layer is impractical since it would cause non-uniformity in shapes and dimensions. Therefore, as an alternative solution, manufacturers usually apply a

modified resin to improve sustainability to the environmental. However, the effectiveness of the modified resin ingredient is questionable since the exposed surface is still unprotected. Instead, besides applying the modified resin system, the contribution of fibres in terms of quantity or volume ratio and arrangement systems in the GFRP materials has also to be considered. With the optimum quantity and proper arrangement system of fibres in the material will probably improve sustainability to the environment or weather. The fibres may act as filler in the material to minimise deterioration effects due to environmental factors or weathering.

It is understood that environmental factors such as temperature, humidity and ultraviolet rays may have some influence on the performance of GFRP. The common features of tropical hot-wet weather in Malaysia are high humidity and frequent sunlight. As the sections are exposed to this weather, their properties may change with time. Thus, this phenomenon will adversely affect the overall performance of GFRP. To utilise the full potential of GFRP sections their response to the weather must be observed. This could be conducted experimentally under indoor and outdoor laboratory studies.

2. EXPERIMENTAL OVERVIEW

The main objectives of the study were to [1]:

- i) observe the effect of continuous glass fibres and orientations on the physical and compression properties of pultruded GFRP,
- ii) investigate the long-term performance of pultruded GFRP exposed to tropical climate, and
- iii) propose an analytical model in GFRP structural design with regard to continuous glass fibres and its applications in tropical climate.

The study was mainly focussed on experimental work in laboratory. The isophthalic polyester resin, Crystic 491E produced by Scott Bader Comp. Ltd., UK was employed. The continuous E-glass type fibres, which were compatible with the polyester resin, were used as reinforcements. The pultruded GFRP plate bars of 76.2 mm width and 6.35 mm thickness were manufactured and supplied by a local fabricator. The plate bars, with light-grey in colour, were fabricated in six-laminate systems consisting of three different single oriented fibre laminates (or single layer fibre laminates) and three different combined oriented fibre laminates (or multilayer fibre laminates) as follows (see *Table 1*):



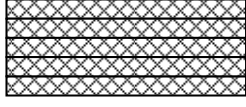

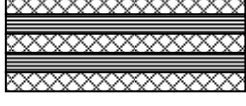

- i) unidirectional roving (U),
- ii) continuous filament mat (C),
- iii) woven roving (W),
- iv) the multilayered fibres of continuous filament mat and unidirectional roving laminate (CU),
- v) the multilayered fibres of woven roving and unidirectional roving laminate (WU),
- vi) the multilayered fibres of continuous filament mat with unidirectional and woven roving laminate (CUW).

All the multilayer fibre laminates were of balance laminate. The samples were prepared in specified sizes to test their physical and compression properties according to the existing standards of practice, such as American Standard of Testing and Materials; ASTM D 3410-87: Procedure B, and British Standard; BS 4618: Part 4: 1972. The experimental program was briefly divided into two major parts. In the first part, the study on initial performance of pultruded GFRP was established by conducting elementary tests on physical and compression properties (see *Table 1*). The second part of the experimental program was exposure tests of

the GFRP samples under out-door tropical climate (see *Plate 1(a)* and *Plate 1(b)*), which was set up after the first part had been completed. Another group of GFRP samples was subject to room environment as a control (see *Plate 1(c)*). The samples were exposed for 3, 6, 12 and 24 months and tested for physical and compression properties. A total of 432 GFRP samples were tested for physical and compression properties, whereby 48 samples for initial performance, 192 samples for exposure tests and the other 192 samples for control (room environment).

For compressive test, samples and test set-up are shown in *Figure 1*, *Plate 2(a)* and *Plate 2(b)*. The 2-mm TML strain gauges were centrally attached and bonded on the gauge region in parallel to load direction to measure strains of both front and back surface of the sample to ascertain that column bending should not be occurred. The strains were recorded by the TML data logger to within 1×10^{-6} strains. The sample was mounted in the compression fixture, which has split collet-type grips. The tabbed parts of the sample were inserted into the grip with the grips in the partly open position. The grips were properly tightened on the sample and set in the position between the load-alignment blocks. The DARTEC Universal Testing Machine with a capacity of 250 kN was set-up for the test.

Table 1: GFRP laminate characterisation for the test.

Laminate Series	Laminate configuration (through thickness)	Fibre Volume Content (V_f), %	Compressive Properties (Initial Performance)					
			Strength, N/mm ²		Modulus, N/mm ²		Strain at failure, %	
			Long	Trans	Long	Trans	Long	Trans
U		50	291	46	39206	4230	0.65	0.99
C		31	79	76	9591	9860	0.48	0.74
W		42	168	61	23949	8921	0.72	0.64
CU		29	155	33	18334	3314	0.83	0.88
WU		50	326	42	36580	5384	0.89	1.14
CUW		40	262	55	26329	6234	1.20	1.01

Note: Matrix volume content = $1 - V_f$; Long = Longitudinal properties; Trans = Transverse properties.

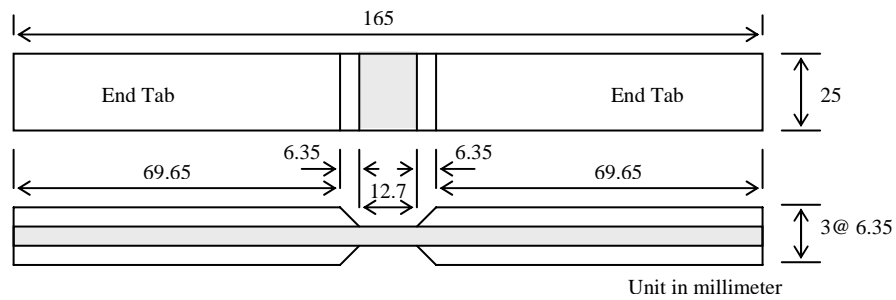


Figure 1: Sample configurations for standard compressive test.



Plate 1(a): Exposure site.



Plate 1(c): Control samples (room environment).



Plate 1(b): Rack and exposed GFRP samples for compressive test.

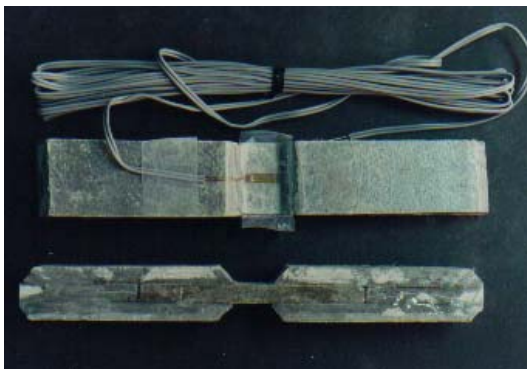


Plate 2(a): Typical samples of compressive test.

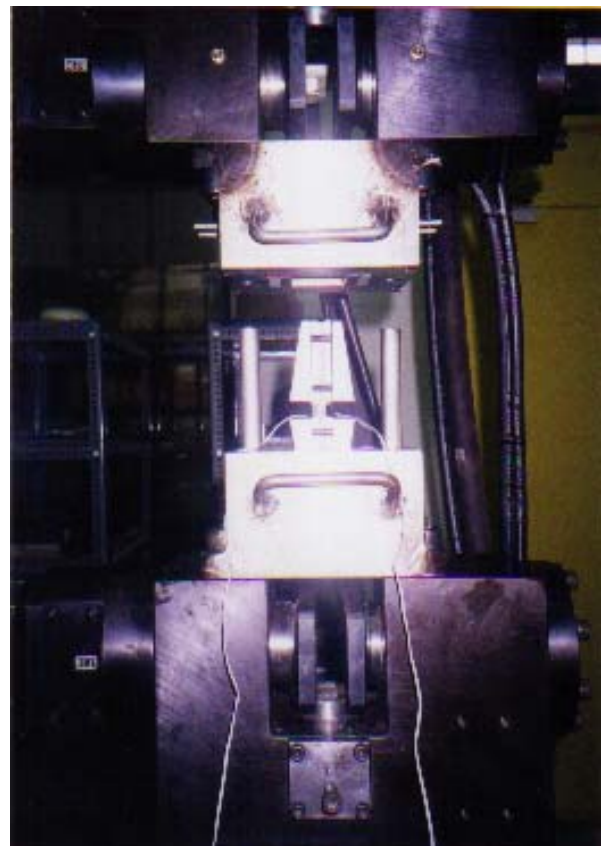


Plate 2(b): Compression test rig.

3. RESULTS AND DISCUSSION

3.1 Physical Changes

The overall photographic views of the typical exposed GFRP samples are shown in *Figure A1*, Appendix. The figure shows the changes on the top surface of samples within 24 months exposure for all series of GFRP samples. The top surface of the GFRP samples, which was horizontally exposed to direct sunlight, was observed to be most affected compared to other surfaces. The control GFRP samples of all the laminate series were observed to be unchanged in physical properties over the specified exposure periods.

The samples degraded due to the attack of environmental agents in atmosphere. It is generally accepted that ultraviolet (UV) radiation, moisture (water), oxygen, elevated temperature and impurities are the main cause of degradation on the exposed polymeric composites [2,3,4,5]. The term degradation is referred to any deleterious change in organic chemical structure, physical properties or appearance of GFRP pultruded composites caused by exposure to elevated temperature (thermal degradation), ultraviolet radiation (photodegradation), oxygen (oxidative degradation) or weathering [6]. The GFRP samples subjected to the weathering exposure might potentially experience those categories of degradations. Although the employment of protective fillers in the polymeric matrix supposed to control the degradation process, but the degree of effectiveness of the material in the real situation is sometimes unknown.

Results after 3 months exposure indicated that there were no significant changes in colour but relatively low degree of surface roughness observed on the exposed GFRP samples. The top and bottom surfaces of most samples were clean, glossy and maintain the original grey in colour. Gloss is a subjective term used to describe the relative amount and nature of mirrorlike (specular) reflection, which can only be traced through naked eye [6]. However, after 6 months exposure, the top surface of all the samples changed slightly in colour, loss its gloss and relatively has a higher degree of surface roughness due to the formation of crazing. Craze (crazing) is a minute surface crack or the multiple surface hairlines cracked that formed on a degraded surface [6]. The colour of exposed surface with originally dark grey changed to light grey. The surface condition was observed chalking with whitish in colour during hot sunny day but relatively clean after raining. Chalking is the formation of a powdery dry, chalk-like appearance or deposited on the top surface of GFRP samples caused by degradation process [6]. This indicated that the loose particles or deposits on the surface were drained and those stuck particles left in place. This process naturally repeated over the period of exposure and appeared the residual material underneath.

After 12 months exposure, further changes in physical appearance at the top surface of GFRP samples were observed considerably with a higher degree of deterioration. The top surface changed in colour from dark grey to light yellowish grey, with loss of gloss, chalking, relatively higher degree of roughness and the fungi randomly grew in the limited area. The W laminate tensile samples slightly warped mainly due to the effect of residual stresses induced in the laminate. Crazing and surface voids also formed in relatively larger amount on the top surface of most of the samples. Growth of fungi on the top surface was considered as the natural phenomenon in moist area where the presence of moisture (water) on the surface attracted free spore in atmosphere and grows. The moisture on the surface accelerated the fungi growth and covered randomly on the affected area. Fibres in the laminates were observed to appear through the surface voids.

Quite significant changed in physical appearance of all the GFRP samples was observed after 24 months of exposure. The top surface of most of the samples experienced severe deterioration when compared to other surfaces. The texture of the top surface became rough and the colour changed to yellowish grey. The fungi spreaded randomly and covered over the surface but lack uniformity between samples. In addition, the W laminate buckled significantly. Some of the fibres were broken and disappeared in the surface due to erosion or

draining, which caused further degradation onto the residual polymer matrix and enhanced debonding process of fibre-matrix interface.

Outdoors elevated temperature, which occurred almost within 20°C in the exposed site as compared to about 4°C indoor environment, might accelerate the chemical reactions involved in degradation and the polymer matrix were most vulnerable in hot sunny climates. In most instances the availability of oxygen was the major factor in the control of chemical degradation. Previous studies found that chemical degradation at different depths within the sample was dependent on the rate of oxygen diffusion through the polymer matrix and on the rate of oxygen consumption [4]. Samples in air at atmospheric pressure and exposed to UV at a level typical of those received outdoors on a hot sunny day, the rate of oxygen consumption near the surface might be sufficiently fast to reduce oxygen penetration beyond a distance of 1 mm or less from the surface to negligible levels. The steep variation in oxygen concentration from the surface did not only cause the extent of chemical degradation to vary steeply but might also alter the kind of chemical change that occurred at different depths. The polymer matrix could undergo both random chain scission and cross-linking or depolymerisation. The discoloration and chalking appeared on the top surface of the samples were the manifestation of the degradation phenomenon. Previous studies also found that the chain scission dominated near to the exposed surface where oxygen supply was plentiful, whereas cross-linking became relatively more probable in the interior where there was less oxygen to compete with radical-radical cross-linking reactions. Radical is an uncharged chemical species possessing one or more unpaired electrons in polymeric matrix. While the cross-linking is the establishing of chemical links between the molecular chains in polymer; when extensive, cross-linking makes one infusible super-molecule of all the chains forming a three-dimensional or network polymer, generally by covalent bonding where can be generated by the influence of heat [6].

3.2 Effects on Compressive Properties

Axial compressive test was also carried out on the exposed and control samples after the specified period of exposure. From the observation, it was found that the compressive stress-strain behaviour of GFRP samples exhibited approximately linear up to the point of failure, which was similar as the initial performance of the materials. *Figures A2(a) to A2(f)*, Appendix, present property retention curves with time of exposure for the compressive strength, modulus and strain at failure, respectively.

3.2.1 Compressive Strength

Due to weathering exposure, the longitudinal and transverse compressive strength of U, WU and CUW laminate improved by 20% to 50% particularly after 12 months exposure. However, a slight reduction by 10% of the longitudinal compressive strength of CUW laminate was observed after 24 months exposure. On the other hand, the C and CU laminates were observed to experience significant reduction in compressive strength in both longitudinal and transverse direction. The C laminate reduced in strength by 10% after 3 months and further reduction up to 37% for longitudinal property and 33% for transverse property over 24 months. The CU laminate reduced in strength less than 10% after 3 month but further reduction up to 31% for longitudinal property and 18% for transverse property over 24 months. The longitudinal compressive strength for CU laminate was significantly affected by the weather as compared to its transverse compressive strength. Meanwhile, the W laminate was observed unchanged in longitudinal compressive strength over 24 months exposure but reduced by 15% after 3 months in transverse property and further reduction up to 44% after 24 months. The transverse compressive strength of W laminate was most affected by the weather over a period of 24 months exposure.

It was obvious that the higher fibre content in GFRP pultruded laminates has increased the compressive strength, even improved its sustainability to the weather. The proper selection on fibre system and arrangement by means of combined fibre orientations in pultruded laminates offers a greater compressive strength and weathering resistance.

However, the effects of weather could increase scattered in the compressive strength data due to the random effects of environmental agents on GFRP samples, as presented by the coefficient of variation values over a period of 24 months exposure.

3.2.2 Compressive Modulus

There was a slight improvement by up to 30% in longitudinal compressive modulus of U, W, CU, WU and CUW laminate over a period of 24 months exposure. However, a reduction in modulus by 10% exhibited by C laminates after 6 months and remained the same up to 24 months exposure.

For transverse compressive modulus, the U and WU laminates improved up to 67% and 10%, respectively, over a period of 24 months exposure. The C laminate initially reduced its modulus by 14% after 6 months but improved gradually up to its initial modulus after 24 months. The similar phenomenon also exhibited by W and CU laminates due to the exposure. In contrast, the CUW laminate initially improved the modulus by up to 33% after 6 months but suddenly reduced by 20% up to 24 months exposure. Except for CUW laminate, other laminates generally improved in the transverse compressive modulus after 24 months exposure.

Scattered in the data occurred for most of the GFRP samples generally after 12 months exposure. The random effect of weathering exposure on the compressive modulus and compressive strength of the GFRP samples was considered very significant.

3.2.3 Compressive Strain at Failure

Effect of weathering exposure on the compressive strain at failure was inconsistent. There was an increase in longitudinal and transverse compressive strain exhibited by U laminate over the period of 24 months exposure. However, the C laminate increased its longitudinal strain by up to 50% but the transverse strain reduced up to 25% over a period of 24 months exposure. The similar phenomenon was also exhibited by WU laminate where there was no significant change in longitudinal strain but the transverse strain reduced by up to 30% over the period of 24 months. Meanwhile, the W laminate exhibited in different behaviour where its longitudinal and transverse strain increased up to 12% and 26%, respectively, over the period of 12 months exposure but reduced up to 11% and 42%, after 24 months. For CUW laminate, the longitudinal and transverse strain reduced by 30% and 10%, respectively, over the period of 24 months exposure. Scattered in the data for most of the GFRP samples obviously increased with the increment of exposure period.

4. PROPOSED MODEL

4.1 Theoretical Development

Results from the experimental study reported that mechanical properties of GFRP generally changed with time due to weathering under tropical climate. Depending on the fibre orientation systems employed in the laminates, the properties, mainly strength and strain at failure, were reduced up to a certain degree. However, some of the properties such as elastic modulus improved over the period of 24 months exposure. The degree of changes or degradation of GFRP mechanical properties is due to weathering, as reported in the previous sections, could be defined as the property retention of the GFRP after the certain period of weathering exposure. The empirical equation, based on the model that has been developed by Chamis and Sinclair for the polymeric matrix under hygrothermal effects, was established to represent the degree of changes of the GFRP property [7]. Since the GFRP materials have been exposed to the weather, where the effects on the properties were expected higher than only the hygrothermal, the model has been modified to develop more comprehensive empirical expression as the followings,

$$P = \lambda_T P_o \quad (1)$$

where,

P = GFRP properties (strength, modulus or strain at failure) after weathering,
 λ_T = the GFRP mechanical property retention ratio after T period of exposure,
 P_o = reference GFRP properties (initial performance) before weathering
correspond to P .

From the inspections, there were three conditions of λ_T could be defined on the property changes, where if $\lambda_T = 1$ as unchanged, $\lambda_T < 1$ as reduction in properties, and $\lambda_T > 1$ as improvement in properties. At time $T = 0$ or before weathering, the value of λ_T was unity. According to BS 4618 [8], the values of property retention of 95% to 105% or λ_T of 0.95 to 1.05 are normally considered to represent unchanged or λ_T as unity. So that, for λ_T greater than 1.05 represents improvement and λ_T less than 0.95 represents reduction in properties.

In design aspect, it is generally accepted that improvement in properties, particularly due to weathering, increases the performance of structures to carry loads. Instead, for the design criteria that often refer to the lower bound theorem, the initial properties of GFRP materials before weathering are utilised. Bogner and Borja applied this principle in their study on the effects of ultraviolet (UV) light on the strength of pultruded composites [9]. Hence, for the purpose of this study, it could be suggested that the properties of those improved due to weathering were considered unchanged by means the property retention of 100% or λ_T was assumed as unity. Therefore, in the following analytical process, the properties those performing reduction or λ_T less than 0.95 will be studied in-depth to clarify the governing factors influenced on the weathering properties of GFRP.

From the study, it was observed that the property retention ratio, λ_T varies with the exposure period, T , and dependent on the type of loading and the characteristics of GFRP materials. In general, the value of λ_T reduced by the increasing of exposure period within the first 6 months and then gradually reduced after the period up to 24 months. Therefore, the relationship between λ_T and exposure period, T could be validated mathematically to establish an empirical model with regards to the weathering effect on the mechanical properties of GFRP. The trend of plot λ_T - T approximately good to fit with the parabolic curve as the function of exposure period as shown in *Figures A2(a) to A2(f)*, Appendix. For more realistic applications it is convenience to express the exposure period as in year. Hence, the changes in mechanical properties of the GFRP due to weathering could be expressed as the function of exposure period by considering fibre orientation systems for the particular loading cases. The expression to establish the λ_T - T relationship could be proposed as the following,

$$\lambda_T = 1 - K\sqrt{T} \quad (2)$$

where, K is the coefficient that, at the first stage of derivation, determines the shape of curve λ_T - T . The value of K can be determined from the slope of quadratic curves of $(1 - \lambda_T)$ versus \sqrt{T} by taking the origin as the intercept of the curves. When K equals to zero, the λ_T - T curve is a straight-line where $\lambda_T = 1$, which means the property is unchanged due to weathering over the period of T year(s).

Based on equation (2), the typical λ_T - T curves for the values of K between 0 to 0.25 and T up to 2 years are shown in *Figure 2*. It can be seen that with the larger value of K the curve exhibits a divergence from the curve when K equals to zero. Based on the trend of the test results, it could be expected that the K values might be governed by the characteristics of GFRP materials and loading types. From the physical studies as reported earlier, the matrix (resin) was significantly affected by the degradation process due to weathering. Hence, it might be meaningful to relate the coefficient, K , with the quantity of matrix $(1 - V_f)$ in the materials, instead of fibre content (V_f) , for the study.

By replacing λ_T in equation (1) from equation (2), a precise empirical expression could be well developed to predict the weathering properties of GFRP materials for any loading cases over the period of T year(s). The expression could be written as the following,

$$P = P_o(1 - K\sqrt{T}) \quad (3)$$

The term in parenthesis of equation (3) is identified as the reduction factor of GFRP mechanical properties. It can be accepted that the values of K are often positive to comply the lower bound criteria in structural design. At the certain period of exposure, the higher value of K indicates the higher degree of weathering effects, which cause a larger reduction in the properties. Obviously, there is a strong relationship between the coefficient K and the degree of weathering effects on the material performance. Therefore, it could be suggested that, to be more convenience hereafter, the coefficient K could be stated as a term, so called *weathering coefficient*. The above discussion has clearly defined the weathering coefficient with regard to the mechanical performance of GFRP materials. In the study, the weathering coefficient of the GFRP could be related to the material performance under the tropical climate.

As reported earlier, the property retention of the control GFRP samples due to indoor exposure was almost within 100% ($\lambda_T = 1$) or unchanged, so that, the weathering coefficient of the control samples was zero. Hence, it could be concluded that there have no weathering effects on the properties as far the materials being properly stored in the room environment.

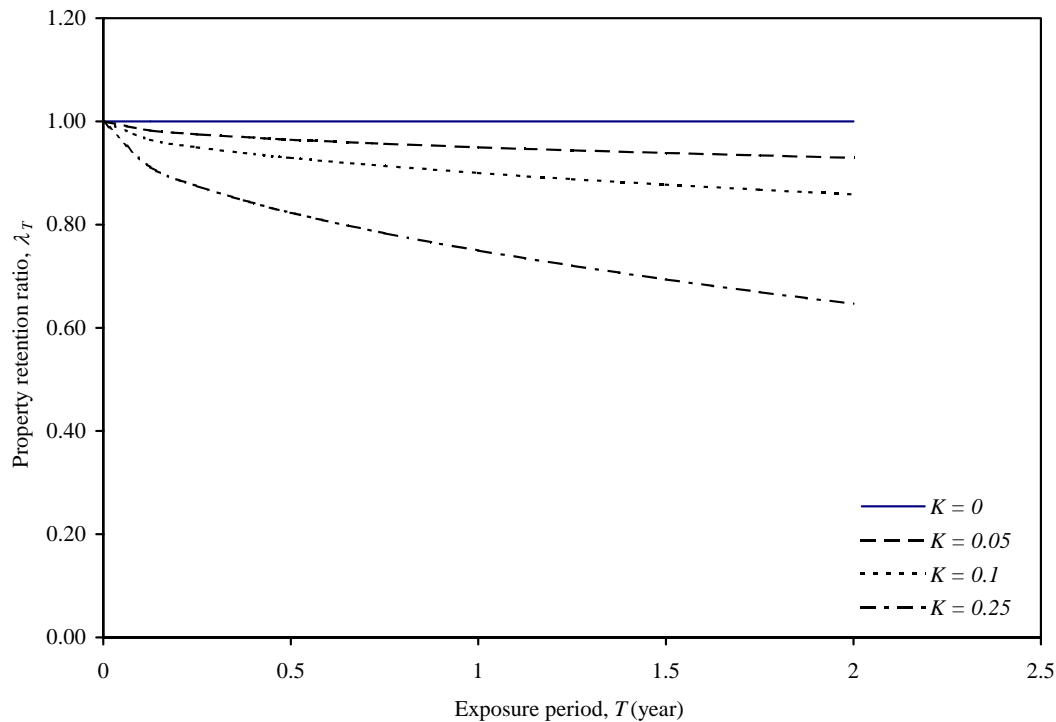


Figure 2: The typical curves of λ_T - T for the values of K within 0 and 0.25.

4.2 Proposed Model for Compression Properties

The weathering coefficient of compressive properties was determined based on the experimental data and the result is shown in Table 2. Let weathering coefficient, K_c for compressive properties and the quantity $(1-V_f)$ was plotted as shown in Figure 3 and Figure 4

to study the degree of weathering effects on the compressive properties and develop an empirical relationship between the weathering coefficient and fibre quantity.

It was found that the weathering coefficient of the compressive strength and elastic properties is dependent on the fibre volume ratio rather than the fibre orientations, as shown in *Figure 3*. In general, the higher the quantity of fibres the lower the weathering coefficient. Obviously, as in the tensile properties, the fibres acts as an inert material in the GFRP laminates, it is being a protective agent to minimise the consequent effects due to weathering. It could also be stated that the effects of weathering were more significant on the matrix than the fibres. The similar trend was also observed in the effect of weathering on the compressive strain at failure of GFRP but with a lower slope of the average $K_c - (1-V_f)$ curve, as shown in *Figure 4*.

Based on *Figures 3* and *Figure 4*, by assuming that the average curves were approximately linear, the expression of weathering coefficient for the respective GFRP compressive properties could be performed as the followings:

For the compressive strength and elastic properties,

$$\begin{aligned} K_c &= 0.571(1-V_f) - 0.275 \\ &= 0.296 - 0.571V_f \end{aligned} \quad (4)$$

and, for the compressive strain at failure,

$$\begin{aligned} K_c &= 0.380(1-V_f) - 0.127 \\ &= 0.253 - 0.380V_f \end{aligned} \quad (5)$$

The slope of the curve of average K_c for compressive strength and modulus was positive. It could be stated that, with regard to the compressive properties, the contribution of fibre in the GFRP laminates to withstand weathering was quite significant.

Table 2: Weathering coefficients, K_c for compressive properties.

Laminate Code	$1-V_f$	Weathering coefficient, K_c					
		Longitudinal properties			Transverse properties		
		strength	modulus	strain at failure	strength	modulus	strain at failure
U	0.50	0.000	0.009	0.000	0.005	0.000	0.005
WU	0.50	0.000	0.003	0.015	0.000	0.000	0.234
W	0.58	0.000	0.032	0.000	0.365	0.133	0.126
CUW	0.60	0.027	0.000	0.191	0.000	0.106	0.056
C	0.69	0.268	0.104	0.268	0.239	0.073	0.141
CU	0.71	0.269	0.003	0.163	0.125	0.050	0.000

Note: V_f is fibre volume ratio.

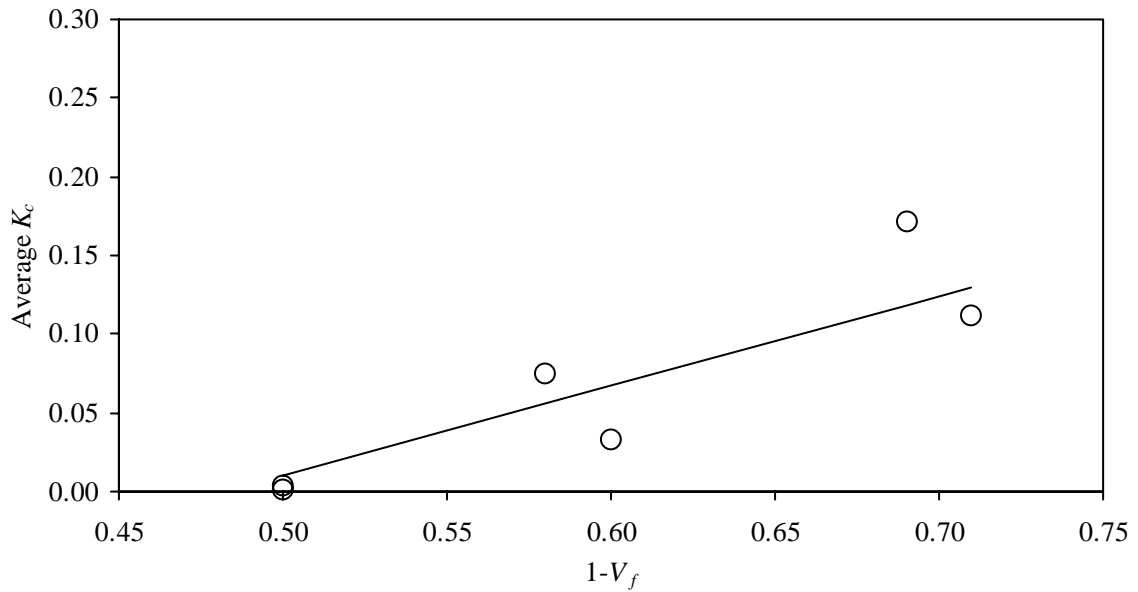


Figure 3: Relationship between Weathering Coefficient (K_c) and Matrix Content ($1-V_f$) for compressive strength and modulus.

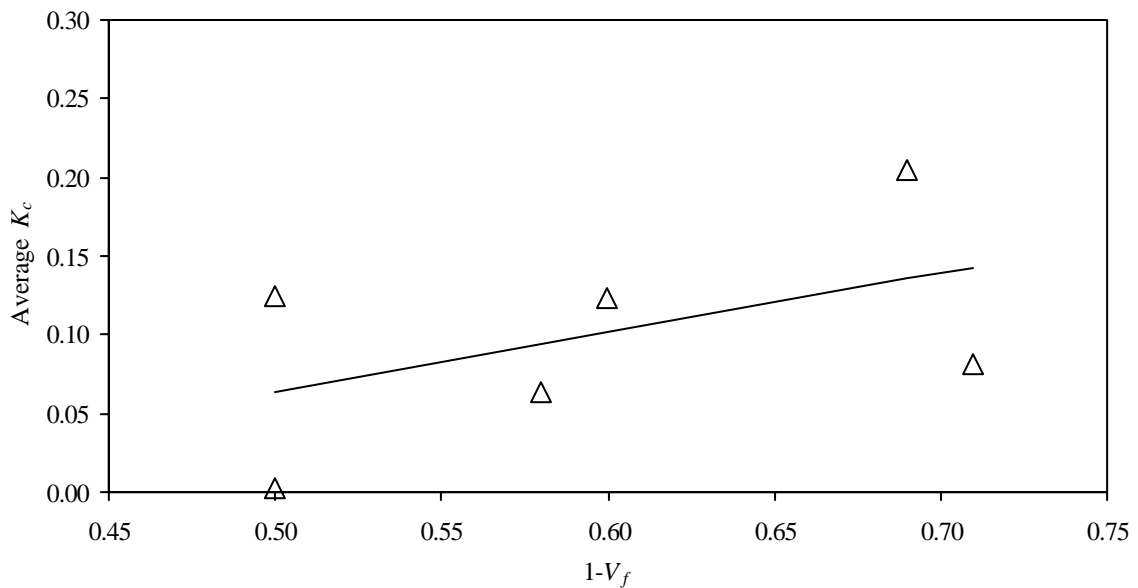


Figure 4: Relationship between Weathering Coefficient (K_c) and Matrix Content ($1-V_f$) for compressive strain at failure.

5. CONCLUSIONS

Based on results from the experimental tests and theoretical development of the pultruded GFRP, the conclusions could be drawn as the followings:

- 1) The pultruded GFRP composites were observed to be affected by degradation process when exposed directly to outdoor tropical weather. This process affected to the physical and compressive properties of the GFRP. Eventually, fibre orientation and age of exposure governed the changes in properties after weathering. However, the control GFRP samples maintained its initial properties even after 24 months indoor exposure.

- 2) The top surface of the GFRP samples was observed to be severely degraded as compared to other surfaces over the period of 24 months exposure. The degree of deterioration was quite significant mostly after 12 months of exposure.
- 3) The property retention of longitudinal compression of GFRP samples was generally dependent on fibre orientation. The longitudinal compressive strength of the GFRP with matrix volume content more than 60% gradually reduced by up to 30% after 24 months exposure, but other laminates were considerably unchanged. However, the modulus retention for all GFRP samples was almost more than 90% and, even majority of GFRP samples improved its modulus property. The reduction in longitudinal compressive strains at failure for most of GFRP samples was observed to be less than 20% of its initial property.
- 4) The changes in transverse compressive properties of GFRP samples with age of exposure were also dependent on fibre orientations in the laminates. Quite numbers of GFRP samples gradually reduced in strength over the period of 24 months exposure, but some others exhibited an improvement in strength. However, the transverse compressive modulus for most of GFRP samples was considerably unchanged over the 24-month period of exposure. The reduction in transverse compressive strains at failure for most of GFRP samples was observed less than 20% of its initial property after 24 months, but the characteristics of strains performance dependent on fibre arrangement and age of weathering exposure.
- 5) The analytical study on the weathering test showed that trend of property retention ratio to the exposure periods fit the parabolic function. Otherwise, the property retention ratio was inversely linear to the square root of exposure period where the slope of the curve was defined as weathering coefficient (K), and the intercept was unity. The proposed models of the weathering effects on the pultruded GFRP materials have been well developed based on the observed trend.
- 6) In general, the strength and modulus properties of the pultruded GFRP materials were affected by the tropical climate up to 24 months exposure. The weathering effect on the GFRP properties, which was already defined as the weathering coefficient, was significantly governed by the fibre content or fibre volume ratio in the materials.
- 7) The weathering coefficient of compressive strength and modulus was inversely linear to the fibre volume ratio of the laminates. The higher fibre volume ratio the lower the weathering effect on the materials. Obviously, the resin matrix was significantly affected due to weathering rather than the fibres. It was also found that the weathering coefficient on the tensile and compressive strain at failure was not governed by the fibre volume ratio in the materials.

6. REFERENCES

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