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Mechanical Property Measurement and Prediction Using Hirsch' s Model for Glass Yarn Reinforced Polyethylene Composite Fabric Formwork

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Abstract

The purpose of this research was to assess the effectiveness of two methods of reinforcing glass yarns, stitching and laminating methods, in a woven (1/1) polyethylene (PE) geotextile fabric used for fabric formwork. Both reinforcement methods improved the tensile properties when the holding load is within the combined breaking load of reinforced glass yarns. However, reinforcing by stitching method provided better tensile properties than the laminating method in respect to creep. The stitched specimens (S-1000 N) and (S-500 N) generated 7.04 mm and 0.53 mm creep respectively compared to the laminated specimens that has produced 7.56 mm (L-1000 N) and 3.11 mm (L-500 N). A Hirsch's model (combined effect of parallel model and series model) was used to predict the modulus of PE + glass yarn composite fabric for stitching method based on the 500 N holding load data. This modulus can be used to calculate the number of glass yarns that should be used in composite for a specific dimension of fabric formwork.

Keywords: Composite; Polyethylene; Glass yarn; Fabric formwork; Hirsch's model; Mechanical property; Lamination and stitching.

Introduction

Fabric formwork is a technology that uses textile fabrics to make molds for concrete casting. Compared to conventional molds that use lumber, plywood and steel, the molds made of fabrics are flexible, easy to use, light weight, permeable and cost less [1]. Other advantages of using fabric formwork include savings in material cost, labour and time [1], rendering blowhole-free smooth surfaces and aesthetic façade impressions [2], resulting in a denser casted surface [3] and extremely beautiful streamline [4-7]. However, due to limited strength and rigidity, fabric formworks are not suitable for large sized structures. Further, when designing the formwork, fabric can only resist tensile forces and cannot retain moisture during concrete curing [8].

Currently, textile woven fabrics (plain: 1/1) are available for fabric formwork and among these fabrics, polyethylene (PE) fabric using various commercial names and patented products is widely used because low cost, lightweight, chemically resistant and durable [8-10]. Further, PE fibre is used in concrete structure to prevent cracking. However, PE is a thermoplastic material that is inherently ductile which causes creep deformation overtime [11]. This creep tendency creates problems in concrete casting. For example, when a concrete column is cast in a tubular PE fabric formwork, due to the hydraulic pressure of the fresh concrete, the bottom section could expand significantly and the column would eventually be out of shape [12]. At the University of Manitoba, the Center for Architectural and Structural Technology (CAST) laboratory is dedicated to research on functional and artistic shapes of architecture object that can be cast from fabric formwork [13]. For fabric formwork, low cost fabric such as PE, polypropylene (PP) and polyester are preferred due to large quantity required in applications. Creep deformation is common in these fabrics and the highest for PE compared to PP and polyester and has been reported as a frequent problem in using a PE fabric for formwork as well as in geotextile applications [14-17].

In concrete casting, the fabric formwork is subject to stress over a period of time. Before the fresh concrete cured to solid form it exerts a constant hydraulic pressure on the fabric formwork [18-20]. Even the pressure, which where resisted by the tensile strength of the fabric, is not high enough to break the fabric it can cause the fabric to creep and expand the dimensions overtime [21-24].

Creep is a very important material property to consider when assessing the effectiveness of textiles as load bearing agents. The conventional stress/strain curve which is commonly used in measuring the strength of a textile fiber is inadequate in measuring creep because when a fabric is used to cast concrete, the instantaneous elastic deformation (IED) and creep together contribute to the overall dimensional change of the fabric [24]. Since IED is almost instantaneous and is inversely related to modulus (stiffness), the change is immediately noticeable and remedies can be made accordingly. Creep, however, is time-dependent and its impact on dimensional change will not show until hours later when the concrete starts to harden. Ideally, both IED and creep of a fabric should be as low as possible to minimize deformation.

When a fabric is used for concrete casts, although the pressure from the fresh concrete is much smaller than its strength, the tendency for the fabric formwork to stretch is still a troublesome phenomenon because, depending on the fabric, it can stretch at a relatively low pressure level. When it does stretch, the dimension of the cast object will deviate from the design parameters.

A potential solution to the problems associated with creep deformation and IED will be to increase the fabric modulus by reinforcing a stiff textile material. The resulting fabric will be low in production cost, stiffer and larger creep resistant, however still be flexible and permeable. A permeable woven specimen would facilitate

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the curing of the concrete by enabling water to bleed out as the concrete hardens [14].

High tenacity technical fibres are used for engineering applications and among all technical fibers, glass fiber is the most commonly used for reinforcement purposes because of its high strength, high modulus, low deformation, minimum IED, near-zero creep, low cost and availability [15]. Traditionally, glass yarns are introduced as the reinforcement by impregnating a sheet of parallel-laid glass yarns in a plastic matrix resulting in a composite material that yields excellent mechanical performance [16]. This type of composite material is widely used to make parts for sports equipment, automobile, heavy-duty machinery, airplanes and mortars [23,24].

The objective of this research is to evaluate and compare two reinforcement methods of glass yarns on PE woven formwork fabric to reduce deformation and increase modulus. The first method was to reinforce a PE fabric by laminating straight laid glass yarn every one-half inch across its 3 inch width. The second method was to affix, by stitching, glass yarns over a PE fabric across its 3 inch width at one-half inch interval. Theoretically, this would impart the necessary rigidity to resist deformation without adding any significant weight.

Materials and Methods

The base fabric for investigation, polyethylene woven fabric (Geotex® 315 ST fabric), was obtained from Propex (Chattanooga, TN, USA). This particular geotextile fabric is used for fabric formwork in CAST lab for concrete casting for more than 10 years. The multifilament C-glass yarn was obtained from Anping Furit Wire Mesh Making Co., (China). The tex of the glass yarn is 320 and contains 200 filament.

Tensile properties of PE fabric and the glass yarns used for reinforcement

The maximum tensile capacity of the original PE fabric was determined by following the procedure set forth in ASTM D5034 [18] with one methodological modification on sample width. Five specimens were subjected to a load at machine speed of 300 mm/min until the specimens broke. To determine breaking force, an Instron 5965 tester was connected to a computer with the Bluehill 2.0 software that recorded data on force, extension and time. The maximum jaw width was 3 inches and the distance between the jaws (effective test length) was 3 inch. The average tensile properties with standard deviation of the original PE fabric are given in Table 1.

The maximum load and extension of the C-glass yarns (320 tex) that were used to reinforce the PE fabric were measured according to the procedure set forth in ASTM D2256-10 [19]. The gauge length specified in ASTM was 250 mm or 500 mm but in this research was reduced to 150 mm because the length of the composite specimens to be tested would be 150 mm in length and have glass yarn reinforcements at the same lengths. Testing the glass yarn's mechanical properties at the same length as their application requirement will better estimate the properties of the glass yarn in the composite phase. Ten specimens of 320 tex glass yarns were tested. The average maximum breaking load, extension at break, maximum strain, instantaneous elastic deformation (IED), IED at zero slope and load at IED with their standard deviations are given in Table 1.

Specimen type	Maximum load (N)	Extension at maximum load (mm)	Maximum strain (%)	IED at zero slope (mm)	Load at IED (N)
PE fabric	3677.1 ± 399.0	26.5 ± 5.8	16.5 ± 3.2	26.5 ± 5.8	3677.1 ± 399.0
Glass yarn	136.8 ± 22.6	4.90 ± 0.46	3.3 ± 0.3	4.9 ± 0.46	136.8 ± 22.6

Table 1: Tensile properties for original (unreinforced) PE fabric and original C-glass yarn.

Measurement of fabric thickness

The thickness of PE fabric was measured using an electronic low pressure thickness meter supplied by Custom Scientific Instrument (New Jersey, USA).

Incorporating the glass yarns into the PE fabric

Two methods were used to incorporate the glass yarns into the PE fabric–by lamination and by stitching them directly onto it.

Lamination

Glass yarn reinforcement tapes were manufactured for lamination: 6 strands of 320 tex glass yarns were placed evenly on the 2 inch width between two sheets of vinyl heat & bound (Iron-on Clear Cover® manufactured by Kittrich Corp) and pressed at about 143°C for 15 seconds to activate the bounding. Then the composite materials were cooled and cut into two strips measuring 1 inch in width and 10 inches in length. Each strip contains 3 glass yarns. The two strips were then glued (Lepage Grey Pres-TITE multi-purpose stray adhesive) onto to the center section of a PE base fabric which has dimensions of 5 inches width and 10 inches length. During the creep test, the laminated samples were clamped between the jaws of the intron testeras shown in Figure 1. The stiffness of the vinyl sheets is assumed to be insignificant compared to the stiffness of the composite material.

Stitching glass yarns onto PE fabric

A piece of Geotex® 315 ST fabric (PE fabric), 5 inches wide and 10 inches long, was reinforced by stitching 6 strands of 320 tex glass yarns within a 3-inch band at its center. The glass yarns were sewn onto the PE fabric using a single needle, walking foot lockstitch machine (Brother Model number: LS2-B837) at 6 stitches per inch along the length. The stitch is classified as 301 according to ASTM Standard [20], with the glass yarns threaded from the bottom bobbin and an all-purpose polyester thread (manufactured by Coats and Clark) threaded from the top needle. The glass yarns were stitched onto the PE fabric

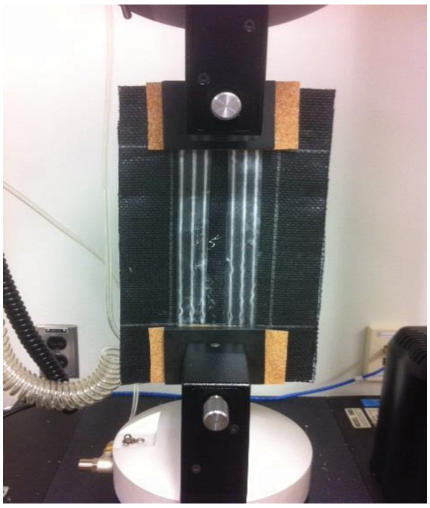

Figure 1: Laminated glass yarn reinforced PE fabric clamped on Instron testing machine.

one-half inch apart and appeared on the reverse side of the PE fabric. During the creep test, the stitched samples were clamped between the jaws of the intron tester as shown in Figure 2. The stitching process was carried out using an Industrial Sewing machine at K9 Storm in Winnipeg, Canada.

Creep tests

The holding load and holding time for the creep test was established according to the failure load and creep rate of the original base fabric. These two parameters were subsequently used in a series of tests to evaluate the properties of the reinforced specimens. These properties included breaking load, elongation, IED, modulus and time dependent creep of specimens.

Establishing time parameter for creep tests

After the test started, the jaws exerted tension force on the specimens and caused them to elongate. About 1,000 seconds later, the creep rates of the original and reinforced specimens stabilized to a much slower rate and continued to elongate at this rate without any fluctuation. Thus, the maximum elongation time deemed suitable for the three specimens was set at creep behavior for 3600 seconds (one hour) to capture the characteristics of time dependent creep properties.

Establishing holding load parameters for creep tests

The breaking loads, extension, IED at zero slope and Load at IED of the PE specimen and glass yarn were measured to determine the holding loads for the tension-creep test. Test results of these values are given in Table 1.

The breaking load of the PE fabric was used to establish the appropriate holding load which was the constant load of tension applied to the specimens for the time-dependent tension creep test on both the unreinforced specimen and the reinforced specimens. For this purpose, a series of holding loads, which were below the breaking load of PE (Table 1), starting from 2000 N, 1500 N, 1000 N and 500 N were applied for one hour. When subject to 2000 N and 1500 N tensile load, the glass yarns in both reinforced specimens broke quickly in the first 30 seconds indicating that they were not strong enough to sustain the tensile loads at these two levels. When the load was reduced to 1000 N, the glass yarns in the laminated specimen (Group L-1000) were able to sustain the load for one hour without breaking. The detail sample identifications are provided in Table 2. However, the glass yarns on the stitched specimens (Group S-1000) continued to break during tests within the first 1000 seconds. When the load was reduced to 500 N, the stitched specimens were able to sustain the load for one hour without breaking. Therefore, 1000 N and 500 N loads were selected as parameters for the creep tests. Notice that the breaking strength of the glass yarn is around 137 N, thus theoretically the total strength that 6 glass yarns alone in each reinforced sample can sustain is around 822 N (Table 1).

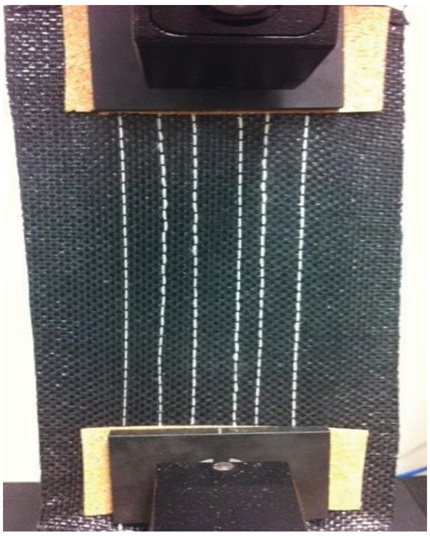

Figure 2: Stitched glass yarn reinforced PE fabric clamped on Instron testing machine.

Statistical analysis

Statistical analysis is conducted using one tailed T test with unequal variance assuming the null hypothesis to be no difference among comparing groups.

Value of t is obtained by:

$$t = \frac{\overline{X_1} - \overline{X_2}}{s_{\overline{X_1} - \overline{X_2}}}$$

$$s_{\overline{X_1} - \overline{X_2}} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}$$

For which $\overline{X}$ is the average value of the sample group, S is the value of standard deviation and n is the number of tested samples, which in this experiment, is 5 for all groups. Degree of freedom m is calculated by:

$1/m = C^2/(n_1-1) + (1-C)^2/(n_2-1)$, which $C = (S_1^2/n_1) / (S_1^2/n1 + S_2^2/n_2)$.

The hypothesis is rejected if t value is greater than the value of $t_{m,\,0.95}$ from the t-distribution table. The values of tm, 0.95 is chosen from the table using the lowest m value calculated among groups to maximizing the value of tm, 0.95 and increase the difficulty to reject null hypothesis.

Results and Discussion

Evaluating the effectiveness of reinforced specimens

To evaluate the effectiveness of the two types of reinforcement, the reduction in total elongation, IED and creep, and modulus of the original PE fabric and the reinforced specimens were measured and compared. Three groups of specimens were tested: Group O represents the original PE fabric; group L represents the laminated specimens and group S represents the stitched specimens (Table 2). The specimens subjected to 1000 N and 500 N holding load were labeled O-1000, O-500, L-1000, L-500, S-1000 and S-500.

Sample type	Reinforcement method	Applied load (N)	Samples identification
Original PE samples	N/A*	500	O-500
Original PE samples	N/A*	1000	O-1000
Glass yarn reinforced samples	Vinyl lamination	500	L-500
Glass yarn reinforced samples	Vinyl lamination	1000	L-1000
Glass yarn reinforced samples	Stitching	500	S-500
Glass yarn reinforced samples	Stitching	1000	S-1000

*N/A: not applicable

Table 2: Reinforcement methods and sample identification.

Elongation properties

All three groups of specimens with two load parameters were tested to measure elongation, strain (%) and reduction in strain (%). Table 3 shows that under a 1000 N holding load, the laminated specimens showed an elongation of 11.41 mm which was lower than the 12.85 mm elongation for the stitched specimens and the 14.13 mm elongation for the original specimen. Furthermore, the elongation of the laminated specimens reduced by 2.72 mm, which was a 19.25% strain reduction from the original specimen at the same load. The elongation of the stitched specimens was reduced by 1.28 mm, which was a 9.06% strain reduction from the original specimen for the same load. The reduction on the total length of elongation was more in the laminated specimens than in the stitched specimens at 1000 N. However, under statistical analysis ($p \leq 0.05$), the differences between groups under 1000 N loading condition were not significant.

Under holding load of 500 N (Table 3), the reduction in elongation and strain (%) were 3.65 mm and 41.76% respectively for the laminated specimens and 5.90 mm and 67.51% for the stitched specimens. It seems that the impact of reinforcement in elongation reduction was more effective under 500 N than under 1000 N. Furthermore, the stitched specimens showed a larger reduction in elongation and strain (%) than the laminated specimens. A plausible explanation is that the stitched specimens were locked in position at every stitch by the top thread leaving the material very little freedom to slip, enabling the glass yarns to prevent the specimen from stretching. Thus, the stitched specimens at 500 N produced a higher elongation reduction of 5.90 mm compared to the laminated specimens at the same load (3.65 mm). The statistical tests comparing the means of elongations among 3 groups ($p \leq 0.05$) showed that group L-500 had significant lower elongation than group O-500, group S-500 had significantly lower elongation than both group O-500 and L-500.

During the tension creep test under 1000 N, the stitched specimens were not able to sustain the tension and eventually broke. Although they all broke within 500 seconds from the start of the test, some broke suddenly and some broke more slowly. The breaking processes of glass yarns were shown in Figure 3. The step-like segments at the beginning (left side) of the time and elongation curve of the S-1000 specimen were caused by the sudden break of some glass yarns in the stitched specimen. Each sudden break released some elongation instantly when the resistance to stretch provided by the glass yarns was diminished and shifted the curve upwards. This phenomenon did not exist in the unreinforced PE fabric (Sample ID: O-500 and O-1000) and the laminated specimens at 1000 N (Sample ID: L-1000) or in all other specimens subjected to 500 N load (Sample ID: S-500 and L-500).

The laminated specimens at 1000 N showed a smooth curved elongation-time relationship (Figure 3) and the elongation was always lower than that for the original and stitched specimens at the same load. This is because the glass yarns were better able to sustain the 1000 N holding load and limited the fabric from stretching. Compared to the breaking test results for glass yarns (Table 1), the average total elongation of the laminated specimens at 1000 N (11.41 mm: Table 3) was much higher than the average maximum elongation of the glass yarns themselves (4.9 mm). The maximum load that the 6 glass yarns could sustain was approximately 822 N.

When pulled by the 1000 N load, the PE fabric was much less stiff than the glass yarns, all tension was primarily exerted on the glass yarns and they should have broken at their maximum capacity of 822 N or their breaking elongation around 4.9 mm. However, the glass yarns in the laminated specimens survived the tension exerted over the duration of the test and reached an elongation of 11.41 mm (Table 3), which was more than twice its maximum elongation. This indicates the likelihood that the glass yarns were slipping under the laminated coating to accommodate the stress and thus avoid being broken. Visual inspection of the laminated samples after testing revealed the formation of crimps by the glass yarns under the coating as shown in Figure 4. When the applied stress is higher than the combined strength of reinforced yarns, the laminated glass yarns can slip without breaking. A similar crimp was developed under 500 N for L-500 samples, but the severity was much less.

Thus, the fact that glass yarns in lamination reinforced specimens could slip under the coating to avoid breakage under overloading gives an advantage that overloading are less likely to cause a dramatic failure in fabric formwork when using a glass yarn lamination reinforced fabric. The disadvantage of such a textile is that it has less creep resistance than the stitched glass yarn reinforcement. On the other hand, the advantage of the glass yarn reinforced textile by stitching method is that if the loading condition is within the glass yarn's breaking load, the reinforcement provides much better creep resistance than the laminated textiles. However, its disadvantage was when overloading happens; there is no mechanism to prevent dramatic failure.

The data in Table 3 show that at both holding loads, the original specimens had the largest average elongation after one hour compared to both reinforced specimens under the same load. The total elongation for Group O-1000 and O-500 was 14.13 mm and 8.74 mm respectively (Table 4).

Instantaneous elastic deformation (IED)

The amount of elongation or extension from start to the yielding point is referred as Instantaneous Elastic Deformation (IED). Figure 5 provides the graphic illustration of and Table 5 shows the IED and yielding point at zero, 80%, 60% and 40% slope thresholds.

In cases where a fibre is plastic in nature, for some samples the zero slope moment may not be detected by the BlueHill® (Instron software). However, the undetected zero-slope moment was estimated by observing the yielding points at 80%, 60% and 40% slope thresholds as shown in Table 4. Subsequently, the IED was approximated from those elongations. For example, in the current research, the zero-slope point could not be detected for some test specimens from the Group

Sample group	Elongation (mm)	Total elongation reduction (mm)	Total strain (%)	% of reduction strain	Initial modulus (MPa)	IED at zero slope (mm)	Creep (mm)
O-1000	14.13 ± 3.64	0	9.42	0	586.85 ± 4.27	8.67 ± 0.34	5.46 ± 3.99
O-500	8.74 ± 2.34	0	5.83	0	532.47 ± 4.77	5.98 ± 0.22	2.76 ± 2.11
L-1000	11.4 1 ± 2.94	2.72	7.61	19.25	1263.52 ± 9.18	3.85 ± 0.15	7.56 ± 3.1
L-500	5.09 ± 1.91	3.65	3.39	41.76	1121.04 ± 5.97	1.98 ± 0.11	3.11 ± 2.02
S-1000	12.85 ± 3.31	1.28	8.57	9.06	903.03 ± 6.56	5.81 ± 0.23	7.04 ± 3.55
S-500	2.84 ± 1.23	5.9	1.89	67.51	898.24 ± 3.26	2.31 ± 0.15	0.53 ± 1.05

Table 3: Changes in mechanical properties under 500 N and 1000 N holding loading condition after 1 hour.

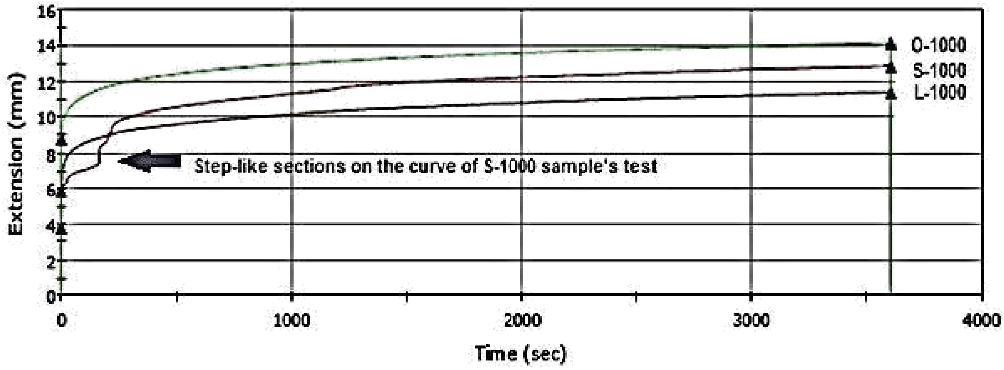

Figure 3: Extension-time curve under 1000 N loading condition tests (for the demonstration purpose curves are selected individual tests which show median results of total elongation in the group to avoid having many curves showing on one graph).

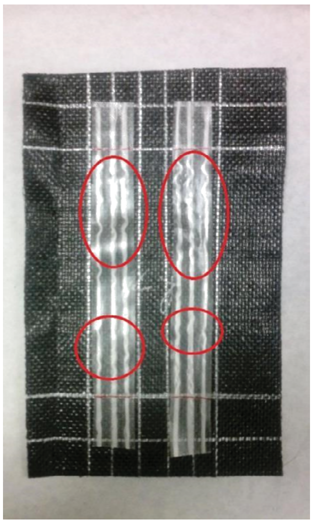

Figure 4: Glass yarns are crimped during the test under 1000 N loading condition (Crimping is marked by the red circles).

Sample ID	IED (mm)	Extension at yield (mm) (zero slope)	Load at yield (N)	Extension at yield (mm) (slope 80%)	Extension at yield (mm) (slope 60%)	Extension at yield (mm) (slope 40%)
O-1000	8.67	8.78	1026.11	8.71	8.71	8.8
L-1000	3.85	3.85	1041.29	3.86	3.96	3.96
S-1000	5.81	5.93	1026.67	2.97	2.97	2.97
O-500	5.98	5.98	499.97	5.97	5.97	6.06
L-500	1.98	Some value not detected	500.77	0.61	1.98	1.98
S-500	2.31	Some value not detected	501.16	0.72	2.31	2.31

Table 4: Yielding elongation at zero slope, 80% maximum slope, 60% maximum slope and 40% maximum slope and load at the yielding points.

S-500. Consequently, the average yielding elongation at zero-slope was calculated by observing the average elongations at 80% (0.72 mm), 60% (2.31 mm) and 40% (2.31 mm) slope thresholds. Since the average elongations at 60% and 40% slope thresholds were identical, the decrease in rate of stretch from 60% to 40% slope threshold occurred at 2.31 mm elongation. Consequently, for the S-500 specimens, the approximate IED is at 2.31 mm elongation at zero-slope (Table 4).

However, Table 4 shows that the load experienced at the yielding elongation is close to the tests' pre-set maximum loads of 1000 N and 500 N. This indicates that the zero-slope was more likely to have been caused by the stopping of the jaws when the pre-set holding loads were reached rather than the sudden increase of the resistance from the specimens when their initial elasticity was exhausted. In fact, the PE original fabric is a thermal plastic material, thus the boundary between elastic deformation and creep does not exist. It was reported that elastic and plastic deformations happen simultaneously for PE fabrics under stress [21]. Thus, the IEDs obtained in this research from the breaking test (Table 1) and creep-tension tests (Table 3) were not strictly elastic deformation; it may have contained some initial creep. Nevertheless, these values reflect the immediate response of the specimens when tensile force was applied, particularly in the fabric form concrete.

Table 4 also shows that all the original specimens produced the

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highest IEDs when compared to other groups under the same loads (1000 N: 8.67 mm; 500 N: 5.98 mm) and all the laminated specimens had the lowest IEDs under both loads (1000 N: 3.85 mm and 500 N: 1.98 mm). All the stitched specimens had medium IED values (1000 N: 5.81 mm and 500 N:2.31 mm).

Changes in creep property

The creep results for the three groups of specimens under 1000 N and under 500 N holding loads are given in Table 3. The laminated specimens under both holding loads produced the highest creep values

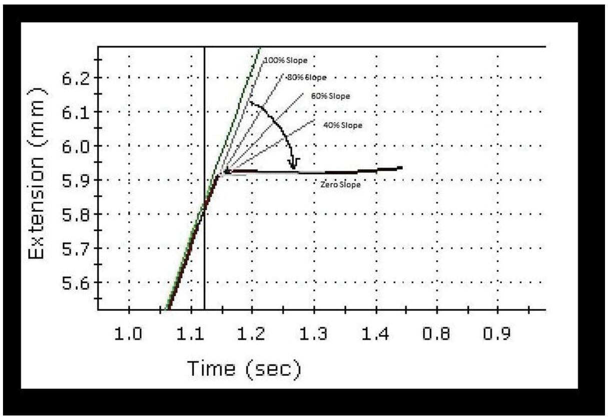

Figure 5: Magnified curve section at the yielding point from curve of Group L specimen. The black triangle mark indicates the yielding point at the zero slope which is a 100% slope drop from the initial slope. Added grey line indicating the initial slope moment (100% slope), 80% threshold slope moment, 60% threshold slope moment, 40% threshold slope moment and zero slope moment.

of 7.7 mm (L-1000 N) and 3.11 mm (L -500 N) respectively. The original specimens under both holding loads produced an average creep of 5.5 mm and 2.76 mm. The stitched specimens under both loads generated 7.1 mm (S-1000 N) and 0.53 mm (S-500 N) respectively.

In the 500 N holding loading condition, the stitched specimens showed more than 80% reduction in creep compared to the original specimen. However, under the 1000 N loading condition the creep of stitched specimens were only 30% higher than that for the original specimens. In contrast, for laminated specimens at 1000 N and 500 N loading conditions, the creep value was increased by 40% and 13% higher than the corresponding original specimens.

Under statistical analysis ($p \leq 0.05$), the differences between groups were not significant for all groups under 1000 N holding loading condition mainly due to yarn slippage in laminated sample and yarn breakage among stitch reinforced sample. There was also not statistical significance among L-500 and O-500 also due to the yarn slippage. However, the significance was found between S-500 and O-500 and S-500 and L-500 specimens.

The differential creep behaviors of glass yarn reinforced PE fabric by stitching method under two holding loading conditions can be explained by the fact that glass yarns broke at 1000 N. When the glass yarns broke, all the stress was transferred to the base fabric and the resistance to stretch provided from the Group S-1000 specimens was no longer better than the Group O-1000 specimens. Additionally, before the glass yarns were broken, the Group S-1000 specimens had lower IED compared to Group O-1000 specimens (IED of Group O-1000: 8.67; IED of Group S-1000 specimens: 5.81; Table 3) and after the glass yarns were broken, the reduced IED that was held by the glass yarns is released to increase the creep. This resulted in the higher creeping rates for S-1000. Under the 500 N holding loading condition, the glass yarns

Glass yarn parameters and equation #		PE fabric parameters and equation #		PE + glass composite and equation #	
Tex	320	Fabric volume width (m)	0.075	Modulus, (*Ec*–upper bound), Eq. # 1	2.089 GPa
Density (kg/m^3)	2460	Fabric length (m)	0.15	Modulus, (*Ec*, lower bound), Eq. # 2	560 MPa
Crosssectional area (m2), Eq. # 4	0.00000013	Fabric thickness (m)	0.0002	Modulus (experimental)	898.2 Mpa (From Table 3)
Strain, Eq. # 5	0.033	Fabric volume (m3)	22.5 E-7		
Stress (MPa)	1052	Vt, Eq. #6	0.9506		
Modulus (GPa)	32				
Volume of 6 glass yarn (m^3)	0.000000117				
Vg, Eq. # 7	0.0494				

Table 5: Experimental and theoretical (calculated using Equations 1 and 2) modulus using series and parallel models.

Number of yarns per 3 inch width fabric	Volume of yarns (10^{-8} m^3)	Volume of the base fabric (10^{-8} m^3)	Relative volume of glass (% *Vg*)	Relative volume of the base fabric (% *Vt*)	Predicted resultant modulus (MPa)
5	9.8	225	0.042	0.958	867.2
6	**11.7**	**225**	**0.049**	**0.951**	***898.7** (898.2)
7	13.7	225	0.057	0.943	926.0
8	15.6	225	0.065	0.935	950.1
9	17.6	225	0.072	0.928	971.9
10	19.5	225	0.080	0.920	991.8
11	21.5	225	0.087	0.913	1010.2
12	23.4	225	0.094	0.906	1027.3
13	25.4	225	0.101	0.899	1043.5
14	27.3	225	0.108	0.892	1058.9
15	29.3	225	0.115	0.885	1073.5

*Calculated modulus in the parenthesis

Table 6: Resultant modulus of glass yarn reinforced composite textile using stitching method (holding load: 500 N).

were able to hold the fabric all the way through the end of the test (3600 sec), and thus limit the creep to a very small amount.

Under both holding loading conditions, the laminated specimens produced larger creep rates than the original specimens. As discussed before, the glass yarns in the laminated specimens had some freedom to slip during the test. Since the laminated specimens always had the lowest IEDs among the groups in the same loading conditions, the remaining unstretched portion of IED was released when the glass yarns started to slip. On the other hand, the original

specimens at 1000 N and 500 N always had the largest IEDs that exhausted a large portion of the total elongation and made the specimen more stable during the creep elongation than Group L-1000 and L-500. This observation of reduced creep rates due to larger IEDs can be made useful in some fabric formwork applications where if it is possible to stretch the fabric before using it may help to stabilize the fabric.

Initial modulus

The initial modulus results for all 6 groups of samples are shown in Table 3. Group O-1000 and O-500 samples produced the lowest average modulus of 586.85 MPa and 532.47 MPa respectively; Group L-1000 and L-500 specimens produced the highest modulus at 1263.52 MPa and 1121.04 MPa respectively; and Group S-1000 and S-500 is in the middle at 903.03 MPa for 1000 N and 898.24 MPa for 500 N loading conditions. Under statistical analysis ($p \leq 0.05$), the differences between groups were significant. These results suggest that reinforcement by stitching (Group S-1000 and S-500) and by lamination (Group L-1000 and L-500) increased the modulus of the specimens. Moreover, modulus increases in the laminated specimens were more than double than that of the original PE fabric and the modulus increase in stitch-reinforced specimens was about 50% more than the original (Table 3).

Generally, if a textile has a higher initial modulus, its stiffness is thus higher. When subject to a tensile load, the elongation is expected to be lower. It was not the case in this experiment under the 500 N loading condition (under 1000 N these parameters were not compared as the glass yarns from S-1000 samples were broken during the test). The Group S-500 specimens produced an average initial modulus at 898.24 MPa lower than the L-500 specimens' average initial modulus at 1121.04 MPa but the average total elongation was 2.84 mm lower than the average elongation at 5.09 mm from Group L-500 specimens (Table 4). This indicates that the Group S-500 specimens were less stiffer than the Group L-500 specimens initially during the IED portion of the elongation, then when the elongation proceed to creep, the stiffness of Group L-500 specimens were lowered and produced a higher overall elongation (IED + Creep).

The reason of the differences and changes in the modulus during IED and creep between these two groups of reinforced specimens could be attributed to the configuration of glass yarns in each reinforced specimen. The glass yarns in Group L-500 specimens were pulled straight, laid flat and laminated while in Group S-500, the glass yarns were not laid as straight as in the lamination method because the during the stitching process, the top polyester thread grabs the glass yarn from the bottom bobbin while it was naturally hanging. When glass yarns were sewn onto the PE base fabric there was some crimp introduced to each stitching. Thus at the beginning of the test, the S-500 specimens had more to elongate than group L-500 specimens which resulted in a lower modulus and higher IEDs. During the tests, because the stitched glass yarns in S-500 specimens were more rigidly bound to the PE base fabrics than the glass yarns in L-500 specimens, as soon as the crimps in S-500 specimens were straightened, the specimens became stiffer than Group L-500 specimens which limited the growth of the creep (which is discussed in the later section) during the rest of the test and eventually resulted in a lower total elongation for S-500 specimens.

The comparison of total elongation, initial modulus, IED and creep for group L-1000 and S-1000 is not discussed because the glass yarns in S-1000 specimens were broken during testing. The elongation property has been improved for both reinforced samples for all loading conditions in the increasing order of S-500 > L-500 > O-500 ($p > 95\%$). As mentioned before even though L-500 had higher modulus and lower IED, the creep development due to yarn slippage underneath the coating caused the total elongation to be higher and thus was out performed by S-500.

Use of Hirsch's model to predict modulus

To reduce the dimension variation in formwork installation, the IED of the formwork can be offset by shortening the dimensions of the fabric used accordingly. The IED can be estimated by predicting the value of initial modulus (Modulus × applied stress = strain, which is IED).

The resultant modulus of a composite material spans a certain range depending on the mechanical interaction between the combined materials. At the upper bound of the range the composite has the highest modulus achieved by perfect bounding which distribute strain evenly within the material. At the lower bound, the composite has the lowest modulus due to complete lack of bounding and strains are developed unevenly under even stress.

The upper bound and lower bound of the theoretical modulus of the composite can be predicted using series and parallel models for two-phase composite materials from the following Equations 1 and 2 [22].

$Ec = Eg \times Vg + Et \times Vt$ → Equation 1 (upper bound assuming perfect bounding, parallel model assuming equal strain), where *Ec* was the modulus of the composite, *Eg* is the modulus of the C-glass yarn, *Vg* is the relative volume of the C-glass yarn in the specimen, *Et* was the modulus of the textile base, and *Vt* was the relative volume of the textile base of the specimen.

$Ec = Eg \times Et / (Et \times Vg + Eg \times Vt)$ → Equation 2 (lower bound assuming nonbonding, series model assuming equal stress), where *Ec* was the modulus of the composite, *Eg* was the modulus of the C-glass yarn, *Et* was the modulus of the textile base, *Vt* was the relative volume of the textile base of the specimen and *Vg* was the relative volume of the C-glass yarn in the specimen.

Furthermore, the following equations were used to calculate the glass yarn parameters, PE fabric parameter and the composite parameters as shown in Table 5.

The total volume of the composite is: $Vt + Vg = 1$ → Equation 3

Cross Section Area (A) = volume / length → Equation 4

Strain = IED / original length → Equation 5

$Vt = V\ base / V\ composite$ → Equation 6 (*Vt* which is the relative volume of the textile base of the specimen i.e., PE fabric)

$Vg = V\ glass / V\ composite$ → Equation 7 (*Vg* which is the relative volume of the glass)

Thus, the upper and lower bound of modulus can be calculated according to the formula to be 2.09 GPa and 560 MPa which was calculated using the equations 1 and 2, which are given in Table 6. The measured average modulus of the specimens from glass yarn reinforcement by stitching method under 500 N loading conditions was at 898.2 MPa (Table 3) and was between the upper and lower bound of the theoretical modulus.

A Hirsch's model [22] for the modulus of the composite which calculates the modulus from a combined effect of parallel model and series model can be established from the equation 8:

$$1/Ec = X\,(1/(Vg * Eg + Vt * Et)\ Parallel\ model +$$

$$(1-X)\left(\frac{V_g}{E_g}+\frac{V_t}{E_t}\right) \text{series model} \quad ---- \quad \text{Equation 8}$$

Where X represent the portion of the effects of parallel model and was calculated to be 0.515 from the tested *Ec* at 898.2 MPa (measured modulus of PE + glass yarn composite, Table 3).

Therefore, according to the model, resultant modulus of the composite with additional glass yarns stitched across the width of the PE fabric was computed according to the volumetric ratio. Table 6 lists the computed modulus for the glass yarn reinforced composite using stitching method for 500 N holding load. It is worth mentioning that the predicted and measured modulus for PE + six glass yarn composite is very close, 898.7 MPa and 898.2 MPa respectively (Table 6).

Application implications

From the breaking test of glass yarns, the average breaking strain of the yarns was found to be at 3.3% (average extension at maximum load/original length at 150 mm). If the PE fabric were reinforced with glass yarns at 6 lines of stiches per 150 mm, the composite modulus predicted was 898.7 MPa (Table 6). Thus, the maximum stress that the reinforced fabric can sustain without breaking the glass yarn reinforcements was calculated at 898.7 MPa × 0.033 = 30 MPa. If also assume a safety factor of 2, the fabric is designed to take 15 MPa stress which can be the maximum allowable *Hoop Stress* (HS) at the bottom of the fabric formwork. Using the liquid pressure of fresh concrete and base fabric thickness, one can calculate the maximum height and radius of the fabric formwork from the following Equation 9:

$$Hoop\ Stressmax_{\max} = \rho gh \times R_{max} / t \rightarrow \text{Equation 9.}$$

Where ρ is the density of the concrete (2400 kg/m^3), g is the gravity (9.806 m/s^2), h is the height of the column or fabric formwork (m), R is the radius of the fabric formwork (m) and t is the thickness of the base fabric (t = 0.0002 m). If a 3 meters high column (fabric formwork) was designed, the hydraulic pressure from the liquid concrete at the bottom section is 0.071 MPa (ρgh). By solving the Equation 9 we can obtain the allowable column radius R_{max} = 0.042 m. Therefore, the Equation 9 can be used to calculate for different diameter and height of the fabric formwork as shown in Table 7.

If the column dimensions are specified with height and diameter, for example, a column with 2 meter height and 0.15 meter diameter (0.075 meter radius) then the required stiffness of the base fabric can be calculated as [(2400 kg/m^3 × 9.806 m/s^2 × 2 m × 0.075 m / 0.0002 m) × 2(safety factor)]/0.033 (maximum allowable strain) = 1070 MPa. Thus the required amount of glass yarn reinforcement per 3 inch width is 15 yarns as indicated in Table 5 (modulus at 1073.5 MPa).

Conclusions

The elongation property has been improved for both reinforced samples for all holding loading conditions in the increasing order of S-500 > L-500 > L-1000 > S-1000 (p > 95%). All reinforced samples showed an improvement in modulus for both holding loading conditions.

Concrete density (kg/m^3)	Fabric thickness (m)	Column height (m)	Column radius (m)
2400	0.0002	3.0	0.042
2400	0.0002	2.0	0.064
2400	0.0002	1.0	0.127

Table 7: Diameter and height of the fabric formwork (Equation 9) (2 glass yarns per inch or 6 for 150 mm).

However, it was observed that the laminated samples produced the stiffer composite due to the straight configuration of glass yarns in the composite fabric. As a result, the modulus of L-500 and L-1000 samples was much higher than the stitch reinforced samples. A significant reduction in IED was noticed for both reinforced samples for all holding loading conditions. This IED value can be considered during the dimension calculation of fabric formwork. The creep has been undesirably increase for both laminated samples and reinforced S-1000 samples due to the slippage and breakage of glass yarns respectively. However, for the S-500 sample, a significant reduction in creep was obtained as the glass yarns' integrity was maintained. It is, therefore recommended that in order to reduce the time dependent creep during fabric formwork, the load should not be exceed the combined breaking load of all reinforced glass yarns. Between these two reinforcement methods, lamination allows more creep but can resist breakage and rupture while the stitching method reduces creep more effectively as long as the loading condition is within the capacity of the glass yarns. Therefore, it can be concluded that stitch method is better than the lamination method. Consequently, for stitch PE + glass yarn composite and 500 N holding load, the Hirsch's model was used to predict the composite modulus from which the dimension of fabric formwork can be calculated. In addition, glass yarn reinforced fabric through stitching method is more cost efficient, has better drape and better permeability than glass yarn reinforced fabric through lamination method.

In general condition, the mechanical properties such as tensile strength, elasticity, shearing resistance and creep rate of a textile woven fabric also depend on the direction of the applied force related to the direction of the weft and warp yarns [25]. The orthotropic property of a conventional textile material is that the strength and the stiffness are at maximum along its weft and warp direction while weaker along off-axes directions [26,27]. Study also showed that maximum stiffness and creep resistance are achieved when a reinforcing material is composited with a woven base fabric according to the orthotropic configuration of the warp and weft because at off-axes direction the low shearing resistance of the woven fabric induces higher plastic deformation [28]. In addition, composite materials have better de-bonding resistance when reinforcement is along the warp or weft direction. In the current study, the reinforcement of glass yarn was conducted in the warp direction, which is justifiable due to the end use of this particular PE + glass composite fabric. The reinforcement may be in the weft direction or in both warp and weft directions depending on the application of the composite fabrics.

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Conflict of Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled "*Mechanical Property Measurement and Prediction Using Hirsch's Model for Glass Yarn Reinforced Polyethylene Composite Fabric Formwork*".

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