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ASSESSMENT OF CREEP ON LONG-TERM PERFORMANCE AND CALIBRATION FACTOR OF GEOSYNTHETICS IN GEOENVIRONMENTAL APPLICATIONS

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Abstract: Geosynthetics became one of the outstanding innovations with ever-growing significance for geotechnical and geo-environmental engineering industry. Earthwork construction over soft polluted sludge lagoons and tailing impoundments is mandatory to cap various waste materials. Low shear strength and high compressibility of such soil deposits expose short and long-term geotechnical challenges. Geosynthetics provide strengthening and allow accessibility over these deposits, which save money and reduce carbon footprint. Like all polymeric products, geosynthetics are susceptible to creep. However, creep data is not published by manufactures for community to disclose stiffness modulus degradation with elapsed time, which is necessary for finite element numerical modelling. This manuscript aims to assess creep effect and derive calibration factor between global to local strains. Field monitoring strain readings of high-elongation gauges glued to geosynthetics must be calibrated against “true” global strain. Geosynthetics polyester (PET) geogrid types Fortrac 35T, 55T, 80T, 110T and 150T were examined at the machine direction under constant strain load ranged from 20% to 0.05% strain/min using the multi-rib tensile method. Correlation charts were plotted to predict stiffness reduction versus logarithm of time. The long-term stiffness value decreases in non-linear manner with increasing logarithm of time but after 1000 hours, is considerably constant of 75% of the secant modulus at 2% strain (working loads). Calibration factor between global to local strains ranged from 2.08 to 1.99 was measured at 2% strain, in agreement with comparable factor of 2.2, which was introduced by Allen et al. (2002). Calibration Factor values slightly increased as strain rate decreased.

Keywords: creep effect, calibration factor, constant strain rate test, geosynthetics, stiffness degradation, global/local strain.

INTRODUCTION

Geosynthetics became one of the outstanding innovations with ever-growing significance for geotechnical and geo-environmental engineering industry. Earthwork construction over soft polluted sludge lagoons and tailing impoundments is mandatory to cap various waste materials. Low shear strength and high compressibility of such soil deposits expose short and long-term geotechnical challenges. Geosynthetics provide strengthening and allow accessibility over these deposits, which save money and reduce carbon footprint. Like all polymeric products, geosynthetics are susceptible to creep. However, creep data is not published by manufactures for community to disclose stiffness modulus degradation with elapsed time, which is necessary for finite element numerical modelling. Advanced numerical analysis in conjunction with proper geosynthetics characterization through

experimental tests are pragmatically deemed to perform accurate representative studies on associated response mechanisms of geosynthetics reinforced soil.

Creep phenomenon is a classically time-dependent elongation aspect for geosynthetics that affect the long-term performance and sustainable durability of the geosynthetic-reinforced structures. Creep impact is also function of the ambient temperature and service life after installation period. Globally, the creep behavior of geosynthetics is somewhat complicated phenomenon, index to the interaction and complexity of the subsequent components: (1) polymer nature and structure, (2) geosynthetics structure (nonwoven, woven, and integral structure), (3) rate of loading/ unloading conditions, (4) temperature conditions, and (5) soil environmental conditions at filed.

Filed monitoring strain readings of high-elongation strain gauges glued to geosynthetics materials must be calibrated against the “true” global strain as reported by Allen et al., (2002). Strain gauges bonded to woven geosynthetics (geogrids or geotextiles) typically generate a local “hard spot” causing under-registration of global actual tensile strains.

Based on series of Constant Strain Rate CSR tests, this manuscript aims to: (a) announce an overview about the geosynthetics behavior, non-linear tensile force– strain relationship (b) assess influence of creep on long-term performance and stiffness degradation, (c) derive calibration factor between global to local strains, and (d) promotes an appropriate geogrid simulation for Plaxis 3D FE modelling that can be used to predict geosynthetics behavior under service loadings rather than incipient collapse.

MATERIALS AND METHODS

a) OVERVIEW

The current research includes laboratory testing for 5 sets of designated specimens of geosynthetics geogrids Fortrac 35T, 55T, 80T, 110T, and 150T with varying strength and stiffness. **Table 1** listed the disclosed physical properties as per the technical data sheet introduced by the manufacturer HUSKER. The standard raw material is the high-modulus polyester (PET), which of high stiffness, low creep, and uniform product strength. The specimens were examined on a tensile test machine under Constant Strain Rate (CSR) in accordance with ASTM D6637, to investigate: (a) creep effect and secant modulus degradation with time and (b) calibration factor between global to local strains.

Table 1: Physical properties for the tested geogrid types as per HUSKER data sheets

PROPERTY	TEST	35T	55T	80T	110T	150T
Ultimate wide width (MD) Tensile Strength (kN/m)	ASTM D-6637	35	55	80	110	150
Elongation at ultimate tensile strength –MD	ASTM D-6637	≤10 %	≤10%	≤10 %	≤10 %	≤10%
Long term design strength- MD (kN/m)	GRI GG4	18.8	29.5	42.9	59	81

b) TEST APPARATUS AND SPECIMEN PREPARATION

TESTOMETRIC M500- 50CT Universal Testing machine was used to perform the geogrid load-extension under Constant Strain Rate CSR. The apparatus comprises main tensile machine, pressure jack and computer control unit. The tensile machine consists mainly of clamps, sensors for recording the tensile force, and other sensors to monitor the extent of grips separation. The clamps must be attached with suitable pressure to avoid slippage. Clamping pressure must be equal for all specimens under the same test to manage consistent judgment between the anticipated results. According to the Multi-Rib tensile method of ASTM D6637 “Standard Test Method for Determining Tensile Properties of Geogrids by the Single or Multi-Rib Tensile Method”; the specimen is schematically illustrated at Figure (1) to be a minimum of 200 mm wide and contains five ribs in the cross-test direction by at least three junctions or 300 mm long in the direction of the testing. The outermost ribs are cut prior to

testing to prevent slippage from occurring within the clamps as instructed by ASTM D6637, clause 8.2.4.

Thus, the width of intact ribs is 120 mm. The room ambient temperature was 20°C during test procedures to avoid adverse impact of the temperature in the test results. Figure (2) shows the particular test setup adopted for derivation of Calibration Factor CF between global to local strains. During the in-isolation tensile testing, strain gauge was mounted on one side of the geosynthetic specimen using soft glue adhesive. A KYOWA gauge type is used with model name KFG-5-120-C1-11L1M2R. Quarter bridge connection was used for 1-gauge 120Ω.

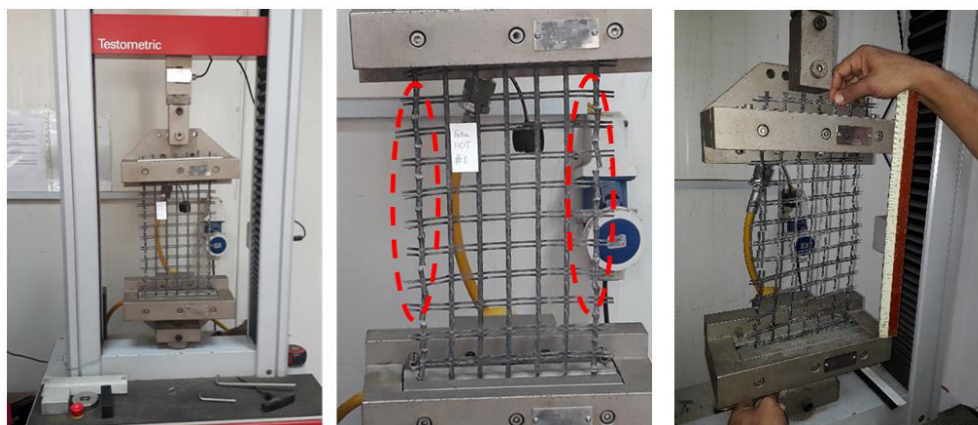


Figure (1): Specimen configuration; Multi-Rib tensile method -ASTM D6637



Figure (2): Test setup for Calibration Factor between local to global strain using CSR tensile test

STATISTICAL ANALYSIS AND GRAPHICAL PRESENTATION

Five single tests were performed on the Machine Direction (MD) for each specimen of Fortrac 35T, 55T, 80T, 110T, and 150T, in accordance with ASTM D6637 using the multi- rib tensile method. Constant Strain Rate CSR of 20%, 10%, 6%, 3%, 1% to slow rate loading 0.05% strain/min. were performed. The sample total width is 200 mm, while the intact width is limited to 120 mm. According to ASTM D6637, clause 8.2.4 “within test methods A, B and C the outermost ribs are cut prior to testing to prevent slippage from occurring within the clamps. For those cases where the outermost ribs are severed, the test results shall be based on the unit of width associated with the number of intact ribs”. Hence, calculation of the secant modulus ($J = EA_1$) at certain strain domain shall be the maximum tensile force divided by the total intact width per meter. For CSR of 0.05%/min, an interval of local strain readings (by automotive data logger) equals to 2 min is utilized to reveal 30 readings through strain domain of 3%. While, for CSR 10%/min, and due to the sensitivity of relatively rapid

test loading; two sets were examined for local strain readings of intervals 2 sec and 1 sec, to result in approximately 30 and 60 readings, respectively to reach the failure.

RESULTS AND DISCUSSION

a. Assessment for variation of stiffness with time (creep)

Creep phenomenon is a classically time-dependent elongation aspect for geosynthetics that affect the long-term performance and sustainable durability of the geosynthetic-reinforced structures. Creep impact is also function of the ambient temperature and service life after installation period.

In general, creep phenomena can be divided into three main phases: (1) Primary creep phase, starts at a rapid rate and reduces with time, (2) Secondary creep phase, has a relatively uniform rate, and (3) Tertiary creep phase, has an accelerating sudden creep rate and ends up by failure of material at rupture time as reported by Han-Yong Jeon (2017).

As geosynthetics are generally manufactured from polymer materials, they exhibit a viscoelastic behavior, time, load, and temperature-dependent, under a sustained constant load. At time t , the total strain $\varepsilon(t)$ can be expressed from the following equation: $\varepsilon(t) = \varepsilon_0 + \varepsilon_I + \varepsilon_{II} + \varepsilon_{III}$. Where: ε_0 is the instantaneous strain and ε_I , ε_{II} , and ε_{III} are the primary, secondary, and tertiary creep strains, respectively. Nevertheless, the final sudden progressive creep strain increase before rupture does not necessarily occur; it is normally revealed for Polyethylene (PE) and polypropylene (PP) not for Polyester (PET) at standard load levels and temperature.

Globally, the creep behavior of geosynthetics is somewhat complicated phenomenon, index to the interaction and complexity of the subsequent components: (1) polymer nature and structure, (2) geosynthetics structure (nonwoven, woven, and integral structure), (3) rate of loading/ unloading conditions, (4) temperature conditions, and (5) soil environmental conditions at filed.

Since the material is a polyester (PET) geogrid, time-dependent stiffness reductions are minimal (approximately 25-15% or less) as concluded by (Allen and Bathurst 2001); as introduced in **Table 2**. Also, temperature sensitivity of PET is not as great as that for HDPE or PP geosynthetics. For typical geosynthetics applications, the ratio of the modulus value at typical working conditions (i.e., strains on the order of 2% and loading times of approximately 1,000 hours) relative to the modulus obtained from typical CRS wide-width test (at strain 10 %/ min. ASTM D 4595) can be estimated for various Geosynthetics polymer types. Allen and Bathurst (2001) introduced a ratio stiffness modulus at 1000 hours $J_{1000hrs}/J_{D4549}$ for polyester (PET) = 0.75 to 0.85.

Table 2: Ratio stiffness modulus at 1000 hours (Allen and Bathurst 2001)

Geosynthetic Polymer	$J_{1000hrs}/$
PP	0.25 to 0.35
HDPE	0.25 to 0.35
PET	0.75 to 0.85

To convert the measured reinforcement strain to the most accurate estimate of the actual reinforcement load, each measured strain to be multiplied by the secant stiffness value that corresponds to the elapsed time. The stiffness value used was taken at a strain equal to the measured strain, but not more than the stiffness value at 1% strain. The time used to calculate the stiffness values was taken with respect to when the layer was installed in the field (Allen and Bathurst, 2014).

Consequently, series of CRS tests were conducted and stress strain curves were obtained for different strain rates of 20%/min, 10%/ min, 6% /min, 3%/min, 1%/min, and 0.05%/min. From the test results and measurement, the loads and time to reach 1% and 2% strains are calculated, and then secant stiffness as well. Long- term stiffness for strain equaled 2% at 1000 hour (creep data from Walters et al.,(2002)) was estimated as 0.75 multiplied by secant modulus at strain 2% measured from CSR of 10%/min (ASTM D 4595). Ratios between stiffness ($J_{2\%}$) to stiffness ($J_{1\%}$) at the same time are evaluated as presented in Table 3. Using average of these ratios, stiffness at strain 1% after 1000 hour can be estimated. The stiffness value decreases with increasing logarithm of time but is reasonably constant after 1000 hours, as reported by (Miyata and Bathurst, 2007).

Table 3: Summary of the derived Secant modulus at 1% & 2% strain for Fortrac 110T, 80T, 55T, 35T, and 150T with elapsed time

	CSR %/min.	time to 1% strain (hr)	time to 2% strain (hr)	Force at 1% strain (kN)	Secant modulus J _{1%} (kN)	Force at 2% strain (kN)	Secant modulus J _{2%} (kN)	Ratio J _{2%} / J _{1%}
110T	20	0.0008	0.00167	17.92	1792	25.34	1267	1.41
	10	0.0017	0.00333	15.83	1583	22.55	1128	1.40
	6	0.0028	0.00556	15.00	1500	21.84	1092	1.37
	3	0.0056	0.01111	13.96	1396	20.86	1043	1.34
	1	0.0167	0.03333	13.54	1354	20.66	1033	1.31
	0.05	0.3333	0.66667	12.08	1208	19.51	976	1.24
	Creep 0.75	1000	1000		1127		846	1.33
80T	21	0.0008	0.0016	11.87	1187	17.97	899	1.32
	10	0.0017	0.0033	11.04	1104	17.37	868	1.27
	6	0.0028	0.0056	10.63	1063	16.11	806	1.32
	3	0.0056	0.0111	10.13	1013	15.48	774	1.31
	1	0.0167	0.0333	9.88	988	15.10	755	1.31
	0.05	0.3333	0.6667	9.17	917	14.97	749	1.22
	Creep 0.75	1000	1000		838		651	1.29
55T	25	0.0007	0.0013	9.24	924	13.47	674	1.37
	10	0.0017	0.0033	7.29	729	10.72	536	1.36
	6	0.0028	0.0056	6.56	656	10.26	513	1.28
	3	0.0056	0.0111	6.25	625	9.90	495	1.26
	1	0.0167	0.0333	5.83	583	9.42	471	1.24
	0.05	0.3333	0.6667	5.21	521	9.12	456	1.14
	Creep 0.75	1000	1000		505		402	1.26
35T	20	0.0008	0.0017	5.80	580	8.84	442	1.31
	10	0.0017	0.0033	5.21	521	7.80	390	1.34
	6	0.0028	0.0056	4.79	479	7.18	359	1.33
	3	0.0056	0.0111	4.58	458	6.96	348	1.32
	1	0.0167	0.0333	3.96	396	6.30	315	1.26
	0.05	0.3333	0.6667	3.96	396	6.20	310	1.28
	Creep 0.75	1000	1000		381		292	1.30
150T	20	0.0008	0.0017	23.75	2375	32.56	1628	1.46
	10	0.0017	0.0033	19.58	1958	27.92	1396	1.40
	6	0.0028	0.0056	18.75	1875	27.56	1378	1.36
	3	0.0056	0.0111	16.67	1667	27.24	1362	1.22
	1	0.0167	0.0333	15.21	1521	25.02	1251	1.22
	Creep 0.75	1000	1000		1362		1047	1.30

For practical use, Figure (3) presents correlation design charts for the assessment of stiffness variation at J_{1%} and J_{2%} strains for the examined specimens versus logarithm of the elapsed time. These charts can be simply used to predict the secant modulus (after creep effect) corresponds to the elapsed time of each geosynthetics geogrid layer during staged construction at filed.

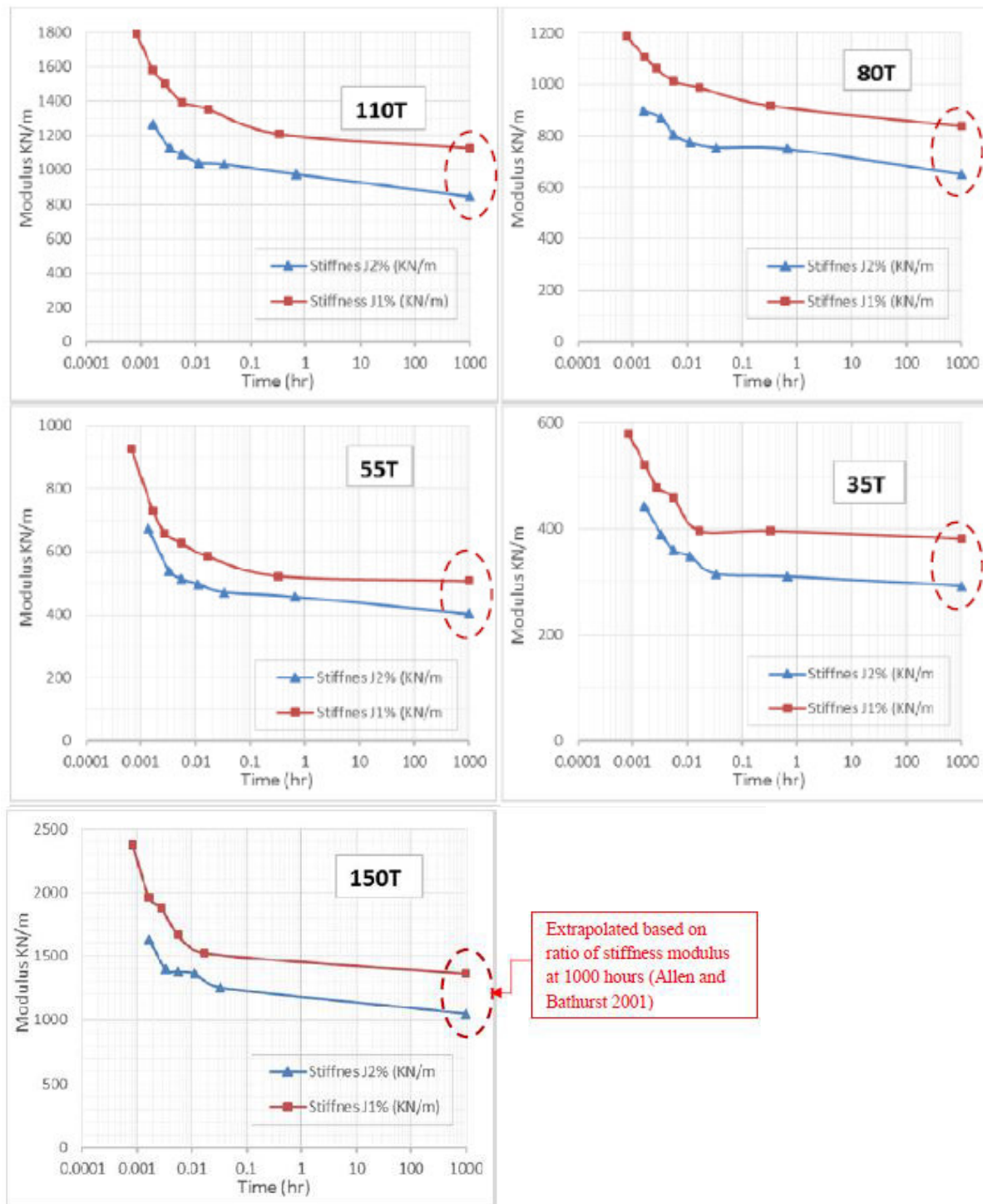


Figure (3): Correlation design charts for variation of secant modulus at 1% and 2% strain with elapsed time for Fortrac 110T, 80T, 55T, 35T, and 150T

Figure (4) demonstrates comparative trend for variation of stiffness with time between 1% and 2% strain for Fortrac 150T, 110T, 80T, 55T, and 35T. The vertical dashed line was plotted for reference to identify modulus J_{D4549} estimated at CSR 10%/min. Figure shows notable behavioural features: (a) non-linear degradation of secant modulus with elapsed time, (b) the derived modulus at strain 1% is larger than corresponding at 2% regardless the strain rate of loading, and (c) the higher the stiffness, the higher the stiffness irrespective to strain rate of loadings.

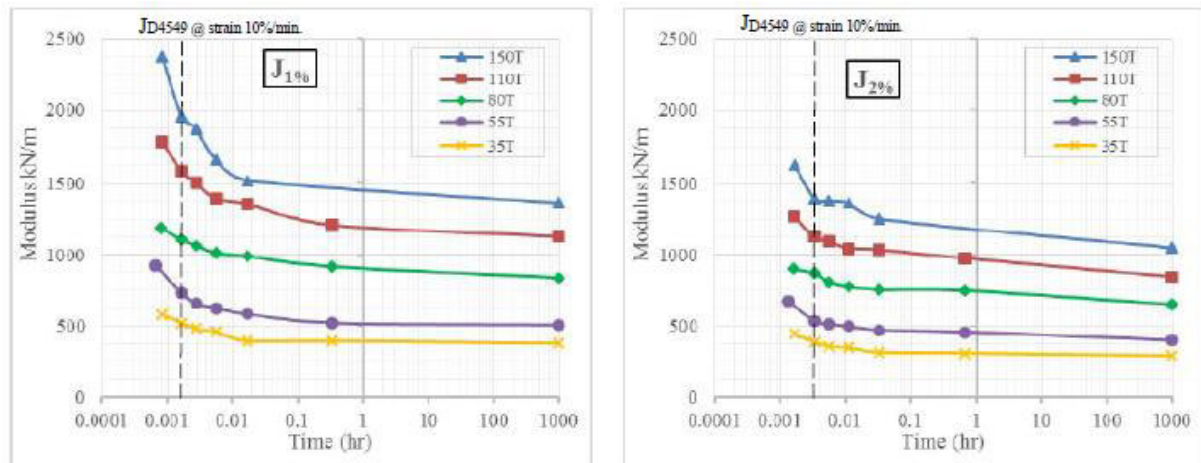


Figure (4): Comparative trend for variation of secant modulus with elapsed time between 1% and 2% strain for Fortrac 150T, 110T, 80T, 55T, and 35T

b. Calibration factor between local to global strain

Strain readings from high-elongation strain gauges glued to geosynthetics reinforced materials must be calibrated against the “true” global strain in the reinforcement as reported by Allen et al., (2002). In the current research, “local strain” or “gauge strain” values denotes strains recorded by a strain gauge at the point of attachment. “Global strain” refers to strain averaged over a length that is much larger than the strain gauge. Strain gauges bonded to woven geosynthetics typically generate a local “hard spot” causing under-registration of global actual tensile strains.

The Calibration Factor CF for a particular combination of gauge, bonding technique, geosynthetics polymer type, and location of gauge is typically established from constant strain rate in-isolation wide-width strip tensile testing in accordance with ASTM D4595 as reported by Allen et al., (2002). Hence, strain gauge readings in the field must be corrected to true global strains by factor derived from in-isolation tensile tests.

In order to better match the realistic (slower) loading conditions of a geosynthetics geogrid layer placed during staged construction, the data from the 0.05 %/min CRS test was used for consistent calibration. The geosynthetics PET geogrid types Fortrac 110T, 80T, 55T, and 35T were tested under CSR of 10%/min as nominal value introduced by ASTM 4595 and at a relatively low strain range of loading 0.05%/min in the domain of 0 to 3% strain, to match the maximum anticipated working conditions under service loadings (no need to reach the strain at break). Strain gauges were mounted on one side of the geosynthetic specimen during the in-isolation tensile testing using quarter- bridge.

For CSR testing of 0.05%/min, an interval of local strain readings equals to 2.0 min is utilized to reveal approximately 30 readings (by automotive data logger) through the strain domain of 3%. While, for CSR 10%/min, and due to the sensitivity of relatively rapid test loading and possible associated missing/ errors for recording the initial significant readings of local strain by data logger; two sets were examined for local strain readings of intervals 2 sec and 1sec, to result in approximately 30 and 60 readings, respectively to reach the failure. However, only limited number of readings (approximate to 10 or 20) at domain of strain 3% is not liable relative to CSR of 0.05%/min.

Figure (5) plotted response curves of the in-isolation local strain versus global strain for various tested specimens 35T, 55T, 80T, and 110T that used to derive the calibration factor. The response curves for constant-rate-of-strain tensile loading fall within a relatively narrow band. The significant under-registration of global strains is considered to be the result of the impregnation of the longitudinal polyester fibre bundles by the gauge epoxy glue, which creates a locally stiff region (hard spot).

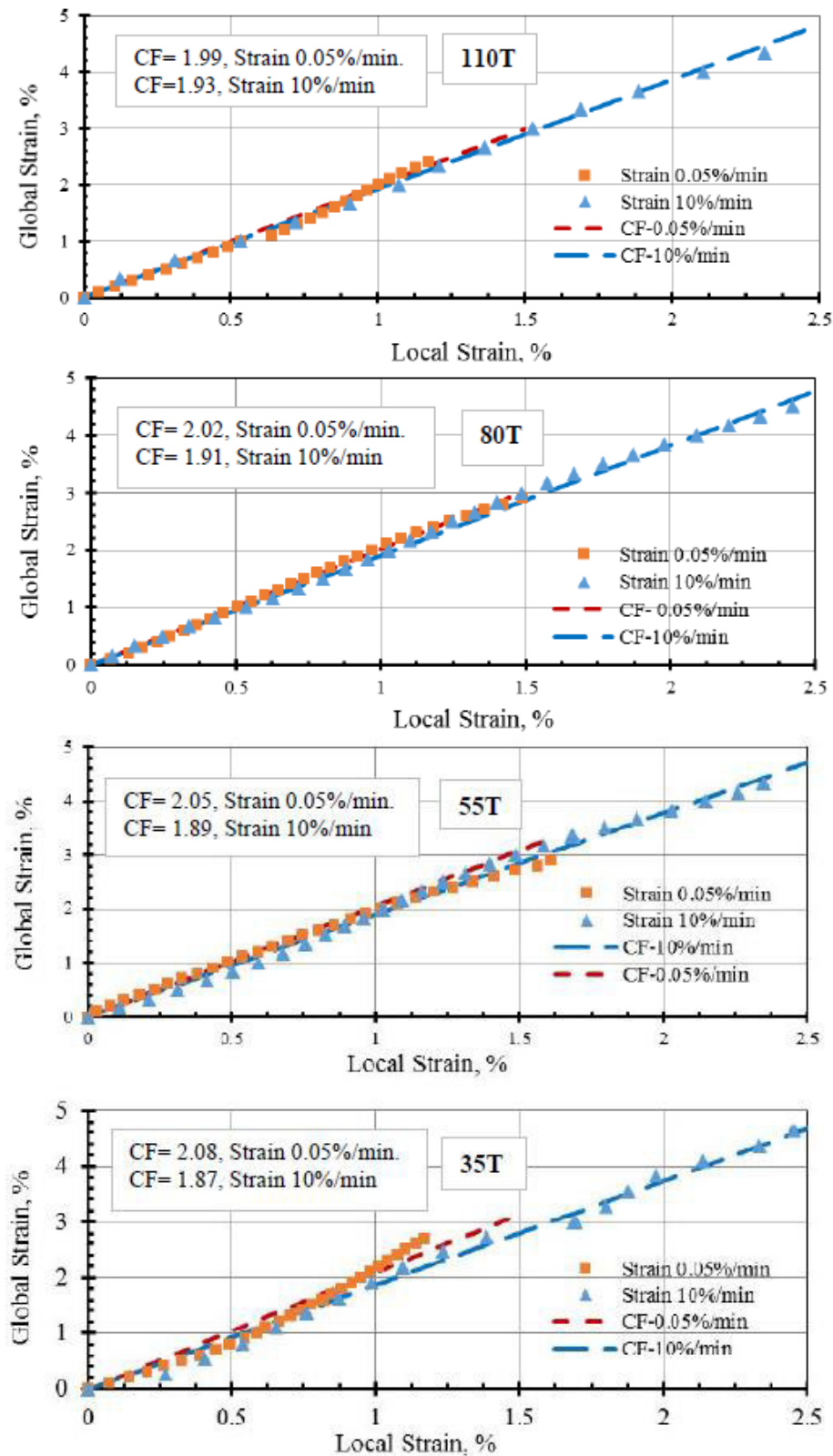


Figure (5): In-isolation local strain gauge response versus global strain for Fortrac 110T, 80T, 55T, and 35T

It should be pointed out that, bonded strain gauges during testing often gave a nonlinear response (or failed in the field) at strains $\geq 3\%$, hence, extensometers acknowledged the sole practical guaranteed devices of measuring geosynthetic strains at large strain domains. Calibration Factor (CF) values slightly increased as strain rate decreased. A nominal average best fit values for CF of 2.08, 2.05, 2.02

and 1.99 were derived appropriate for such foil strain gauges glued to Husker PET geogrid type 35T, 55T, 80T, and 110T, respectively. A single-value calibration factor from this data over a range of 0 to 2% strain is approximately 2. In other words, the strain gauge values must be doubled to represent “true” global strains. This CF estimation for strain levels $\leq 2\%$ is in worthy agreement with comparable PET geogrid CF of 2.2, which was introduced by Allen et al., (2002). It can be argued that the actual loading history of a geosynthetics reinforcement layer during construction falls between the two idealized loading conditions performed in the laboratory.

It was identified that, to adapt the measured reinforcement strain to the most accurate estimate of the actual reinforcement load, each calibrated measured (global) strain to be multiplied by the secant stiffness value that corresponds to the elapsed time (after considering creep effect). The time used to calculate the stiffness values to be taken with respect to when the layer was installed in the field (Allen and Bathurst 2014).

c. Geosynthetics simulation at numerical plaxis 3d model

Principally, no successful mechanical model is yet introduced to properly identify the extensible polymeric reinforcement geogrid load as reported by Bathurst (2019). However, the linear approximation of secant modulus (after creep consideration) is considerable accepted in the strain domain up to 2% which covers a wide scatter of working conditions under service loadings as concluded by Hatami and Bathurst (2005). The geogrid characterization findings derived from the CSR testing are usually used to simulate the mechanical properties of the geogrid used at Plaxis 3D numerical FE modelling. The linear “Elastoplastic- anisotropic” geogrid model introduced by Plaxis 3D seems appropriate to numerically simulate the geosynthetics behavior under service loadings. The derived parameters for the examined specimens are listed at Table 4.

Table 4: Elastoplastic- anisotropic geogrid parameters to be adopted at Plaxis 3D model

Type	35T	55T	80T	110T	150T
EA ₁ (kN/m)	369	500	738	948	1186
EA ₂ (kN/m)	3.69	5	7.38	9.48	11.86
GA (kN/m)	1.845	2.5	3.69	4.74	5.93
N _{p,1} (kN/m)	18.8	29.5	42.9	59	80.6
N _{p,2} (kN/m)	0.188	0.295	0.429	0.59	0.806

Where:

EA₁ and N_{p,1} denote secant modulus and long term design strength at Machine-Direction MD, respectively derived based on the undertaken CSR test results. To simulate the uniaxial geogrid behavior, the secant modulus EA₂ and Long term design strength N_{p,2} in cross machine direction CD to be introduced equal to 0.01 of that corresponding to MD to avoid numerical errors. Moreover, shear modulus GA is assumed equals to half of secant modulus EA₂ in cross-machine direction CD.

CONCLUSIONS AND RECOMMENDATIONS

The current paper focuses largely on, how to better identify the short and long –term response and material characterization of geosynthetics polyester (PET) geogrid under service loadings rather than incipient collapse. Like all polymeric products, geosynthetics are susceptible to creep. However, creep data is not published by manufactures for community to disclose stiffness modulus degradation with elapsed time, which is necessary for finite element numerical modelling. This manuscript aims to assess creep effect and derive calibration factor between global to local strains. Field monitoring strain “local” readings of high-elongation gauges glued to geosynthetics must be calibrated against “true” global strain. Hence, sets of geosynthetics polyester (PET) geogrid specimens Fortrac 35T, 55T, 80T, 110T, and 150T were examined at the Machine Direction MD under Constant Strain Rate CSR

loading tests, in accordance with ASTM D6637 using the “multi-rib tensile” method. A series of CRS tests were conducted wide strain rates of 20%/min. (relatively high rate), 10%/ min, 6% /min, 3%/min, 1%/min, and 0.05%/min (relatively slow rate). Correlation design charts were plotted to predict stiffness modulus reduction versus logarithm of elapsed time. The main outcomes are as follows:

- The measured tensile force –strain relationship exposed a non-linear response of the examined geosynthetics PET geogrid specimens.
- The long-term stiffness value decreases in non-linear manner with increasing logarithm of time but after 1000 hours, is considerably constant of 75% of the secant modulus at 2% strain (working loads). Outcome is in good agreement with consensus that, for polyester (PET) geogrid, time-dependent stiffness reductions will be minimal (approximately 25-15% or less).
- The linear approximation of secant modulus after creep consideration is considerable accepted in the strain domain up to 2% which covers a wide scatter of geosynthetics reinforced structures conditions under service loadings.
- The derived stiffness at 1% is larger than corresponding for 2% strain, which reflects phenomenon of non-linearity and stiffness relaxation with progressive elongation.
- Strain gauge readings of geosynthetics measured in the field must be corrected to true global strains using in-isolation tensile response derived from the constant strain rate CSR loading tests of the instrumented specimens. Strain gauges bonded to woven geosynthetics typically generate a local “hard spot” causing under-registration of global actual tensile strains.
- Calibration Factor CF between global to local strains ranged from 2.08 to 1.99 was introduced appropriately for the tested polyester geogrid specimens at stain domain of 2%. In other words, the strain gauge measured values must be doubled to represent “true” global strains. This derived CF estimation for strain levels of 2% or less is in worthy agreement with comparable PET geogrid CF of 2.2, which was introduced by Allen et al. (2002).
- Calibration Factor values slightly increased as strain rate decreased. For example; specimen 35T; derived CFs are 2.08 and 1.87 for strain 0.05%/min. and strain 10%/min, respectively. Nevertheless, the CF derived based on the slow rate of strain loading 0.05%/min. seems appreciate to simulate the actual loading conditions and staged construction at site.
- Bonded strain gauges during testing often gave a nonlinear response (or failed in the field) at strains $\geq 3\%$, hence, extensometers acknowledged the sole practical guaranteed devices of measuring geosynthetics strains at large strain domains.
- Linear “Elastoplastic- anisotropic” geogrid model promotes by Plaxis 3D seems appropriate to numerically simulate the geosynthetics behavior under service loadings (strain domain $\leq 2\%$) after considering the stiffness degradation associated with creep effect. Sample set of admitted parameters were endorsed to be adopted at Plaxis 3D modelling of geosynthetics.

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