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TECHNICAL NOTE

Experimental Investigation of the Tensile Response of Stiff Fiberglass Geogrid Under Varying Temperatures

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Abstract

Soil reinforcement placed at shallow depth below ground surface is usually exposed to seasonal variation in temperature that can affect the mechanical properties of the material, particularly in cold climates. It is, therefore, essential to understand the effect of temperature on the tensile response of geosynthetic material and consider these effects in the design of reinforced soil structures built in these extreme environments. High-strength fiberglass geogrids are relatively new reinforcement materials that have enhanced properties with a potential use in a wide range of applications. To measure the effect of temperature on the material's ultimate strength, strain at failure, and modulus of elasticity, 48 tensile tests were carried out at different temperatures that range from – 30 to 40 °C following ASTM D6637. The results indicated that the ultimate tensile strength and modulus of elasticity increased by about 24% as the ambient temperature decreased from room temperature to – 30 °C. However, the tested samples showed no significant in the measured strain at failure. It is also found that, for the range temperatures considered in this study, the strain at ultimate strength did not exceed 2%, which is significantly lower than that reported for comparable geogrid materials.

Keywords Fiberglass geogrid · Temperature · Tensile strength · Cold temperature · Mechanical properties

Introduction

Geosynthetic materials are widely used to enhance the engineering properties of soils under different surface loading conditions. In many of these applications, e.g., embankments, slopes, retaining walls, and foundations, the reinforcement materials are generally installed near the ground surface and are, therefore, subjected to ambient temperatures that can vary significantly during the life span of the structure [1, 2].

Research on ground temperature [3] revealed that in regions where there is relatively deep and continuous winter snow cover, the mean ground temperature may be higher than the mean annual air temperature by as much as 5 °C. In coastal regions, however, the difference is usually not more than 1 °C. An example that shows the range of ground temperature with depth is shown in Fig. 1. The presented annual ground temperature data was directly measured to support the design, construction, and operation of the Mackenzie Valley Pipeline near Northern Alberta, Canada [4]. The seasonal variation is found to generally decrease with depth with maximum variation in temperature near the ground surface. For reinforcement material (e.g., geogrid) installed at relatively shallow depth, the effect of ambient temperature on mechanical properties, i.e., tensile strength and modulus, need to be assessed. Moreover, in areas with extreme seasonal variations in temperature, it becomes critical to understand and assess the effect of this variation on the mechanical properties of the geogrid material.

It has been reported that the properties of a geosynthetic material may change during its service life due to several factors, including mechanical stresses and thermal effects [5]. For example, polymeric geogrids may lose part of their

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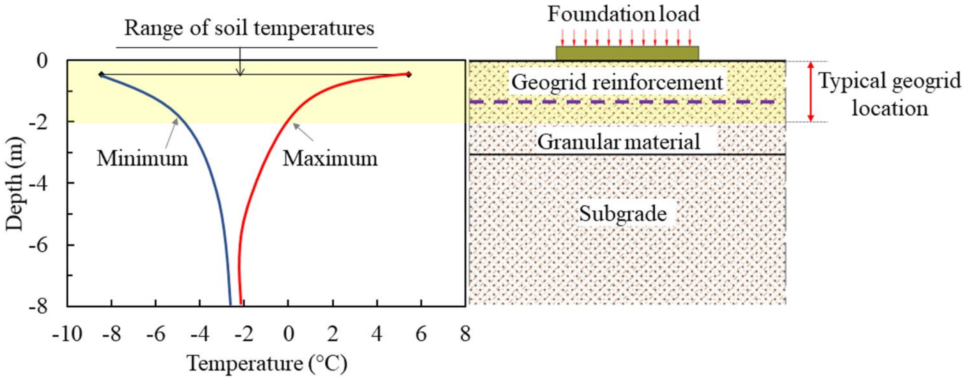


Fig. 1 Typical distribution of ground temperature with depth and the range of temperatures acting on a reinforced soil layer

tensile strength at elevated temperatures due to the inherent physico-chemical properties of the material and the thermally induced relaxation effects [6]. Polymeric materials used to manufacture geogrids usually have temperature-dependent mechanical properties. At low temperature, their molecules have limited ability to rearrange themselves when subjected to an applied load, transitioning into a glassy stiff material with brittle response to loading. As the temperature increases and exceeds the material's glass transition temperature, the molecules are able to reorient themselves more easily, which results in more ductile behavior [7–9]. Therefore, understanding the impact of temperature variations on the tensile strength of geosynthetics is essential for long-term design. Researchers recommended that the properties of geosynthetics should be evaluated at different ambient temperatures and a proper safety factor need to be incorporated into the long-term design of the geotechnical structure [10].

A considerable number of studies have been performed over the past few decades to examine the effect of temperature on the behavior of geotextiles [11–13]. Calhoun [12] tested six polypropylene (PP) geotextiles at temperatures ranging from – 18 to 82 °C. It was concluded that the effect of temperature change on the tensile strength of the tested materials is generally insignificant, however, the decrease in temperature resulted in a reduction in the sample elongation at failure. Bell et al. [13] tested five different types of woven geotextiles (slit film PP, needle-punched PP, heat-bonded PP, needle-punched polyester, and resin bonded polyester) subjected to different environmental conditions (e.g., dry, in freshwater, and in saline water) at temperatures that range from – 12 to 22 °C. Under the investigated temperatures, little change was reported in the tensile strength; however, the strain at failure decreased at low temperature except for the case of needle-punched polyester geotextile.

Ariyama et al. [14], Al-alkawi et al. [15], Li et al. [16], and Ghazizadeh and Bareither [17] tested multiple materials, including, polypropylene woven polymer composites, glass fiber polymer, and needle-punched geosynthetic clay liners at above zero temperature. It was concluded that tensile strength generally decreased with the increase in temperature for all tested materials. Similarly, Zornberg et al. [18] and Koda et al. [19] tested different samples of woven geotextile at above zero temperatures. The results showed that the tensile strength decreases with the increase in temperature. Koda et al. [19] showed experimentally that tensile strength decreased by about 34% when the temperature was increased from 20 to 80 °C. Kasozi et al. [20] and Chantachot et al. [21] tested high-density polypropylene geogrid (HDPE) at temperatures that range from 20 to 60 °C and from 30 to 50 °C, respectively. They concluded that the tensile strength of the tested HDPE geogrid decreases, while the ultimate strain increases with the increase in temperature. A similar conclusion was reached by Chantachot et al. [22] after testing two different polymeric geogrids (HDPE and PP) at temperatures 30°, 35°, 40°, 45°, and 50 °C.

Researchers also conducted tests to study the response of geosynthetics when subjected to only negative temperature. Torabizadeh [23] investigated the tensile behavior of glass fiber (GF)-reinforced epoxy matrix composites at room temperature (25 °C), – 20 °C, and – 60 °C. The tensile test results showed that the material stiffness and strength increased with the decrease in temperature. SGI Testing Service [24] reported the tensile properties of 24 samples of uniaxial polyester (PET) geogrid (TE-UX200PET) at – 20 °C and 20 °C. Results showed that the tensile strength and strain at failure decrease with the decrease in temperature.

Hsieh and Tseng [25] tested six samples of PVC-coated polyester geogrids under temperatures ranging from 0 to 80 °C following ASTM D6637-B. The results revealed that the sample strength increased with the increase in temperature, which contradicts the findings of the previously mentioned studies [14–23]. The rate of change in strength is found to be about – 0.33%/°C.

Recently, Desbrousses et al. [11] investigated the effect of temperature, ranging from – 30 to 40 °C) on the mechanical properties of two polymeric geogrid materials: biaxial polypropylene geogrid and biaxial polypropylene composite with non-woven polyester geotextile. The work concluded that the response of polymeric geogrids to tensile loads is considerably affected by temperature. The geogrid composite showed insignificant temperature-induced changes in tensile strength.

Although the above studies provided an important insight into how the mechanical properties of geosynthetics can be impacted by the change in temperature, most of these studies focused on polymeric geogrids and geotextiles. Therefore, there is a need to expand these studies to cover emerging new materials such as stiff fiberglass geogrid. It is also noted that most of the reported results do not cover a temperature range that allows one to compare the combined effect of both above and below zero temperatures. The objective of this study is to investigate the effect of temperature variation on the mechanical properties of stiff fiberglass geogrid. The measured stress–strain results are presented for temperature range is from − 30 to 40 °C and the mechanical properties, typically used in design, are then discussed.

Experimental Program and Test Procedure

Tested Material

The material tested is stiff biaxial fiberglass geogrid (Con-Force grid TE-SCR150) with rib thickness of 0.9 mm and width of 4 mm. The aperture size of this geogrid is 35 mm × 35 mm. The material is made of high modulus fiberglass with a durable polymeric coating. As reported by the manufacturer [26], the strain at ultimate stress is less than 2.9% with secant modulus of 2800 kN/m at 0.5% strain. The melting point of the material is reported to be less than 820 °C. To prepare the material for testing, single-rib samples measuring 250 mm in length were cut from a large sheet of the geogrid material. Figure 2 shows the fiberglass geogrid sheets and a sample used in the experimental work.

Test Setup and Procedure

The experimental work focused on determining the ultimate tensile strength and strain at different temperatures to study the effect of the temperature on the mechanical properties of the fiberglass geogrid. Figure 3 shows the test setup and the environmental chamber used to carry out the experiments. The experimental setup consisted of a computer-controlled MTS loading frame with 5 kN capacity grips. The setup hosts a 250 mm wide, 810 mm long, and 230 mm-deep temperature chamber such that single-rib tensile tests can be performed on geogrid samples over the range of target

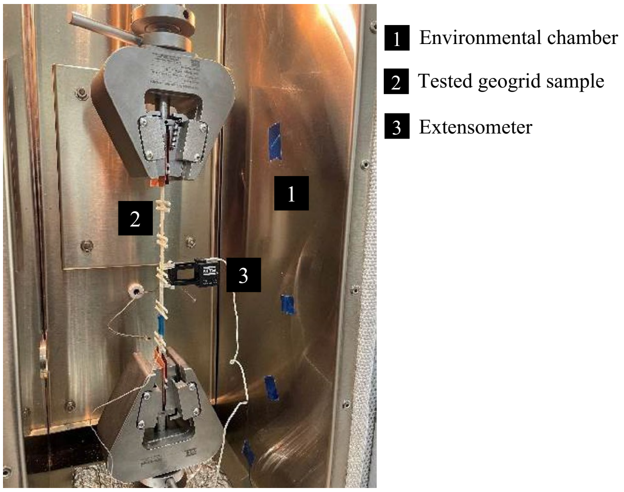
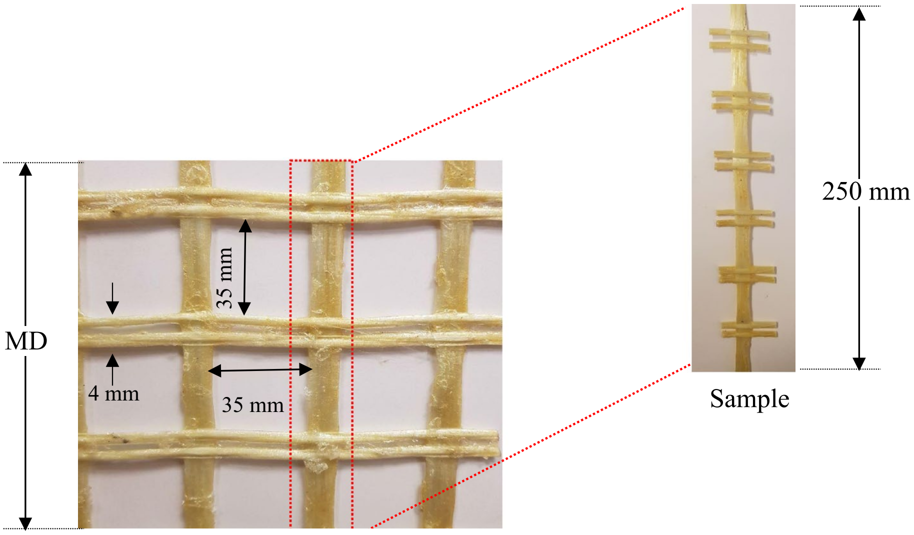


Fig. 3 The test setup used to carry out the experiments

Fig. 2 Portion of the fiberglass geogrid sheet and the tested sample



Portion of the 500 mm × 500 mm geogrid sheet temperatures. Given the chamber's internal dimensions, only single-rib tests can be accommodated. The target temperatures were maintained in the environmental chamber by means of a built-in heating system and an external liquid nitrogen cooling system. The temperature chamber was also fitted with a fan that was constantly operating during the experiments to ensure uniform temperature distribution. The temperature inside the chamber as well as on the geogrid samples was monitored using thermocouples taped to both the surface of the sample and the internal walls of the chamber. The tensile tests were initiated once the temperature on the sample's surface reached the target temperature. The test duration varied depending on the target temperature.

Single rib tensile tests are performed as per the requirements of ASTM D6637-Method A [27], which involves applying an increasing load to the tested samples up to failure. The objective is to determine the maximum tensile load that can be carried by the geogrid samples at different temperatures. Prior to the start of each tensile test, a small preload of 15 N is applied axially to the sample to minimize the possible settling error. The tested sample is attached to the mechanical jaws, which operate at a constant strain rate of 10 ± 3%/min. Two sandpaper sheets were placed on both sides of the geogrid being clamped by the mechanical wedges to minimize slippage. An MTS 632.11F-90 extensometer was used with a gauge length of 25 mm and operating temperature ranging from − 100 to 150 °C. The force and the corresponding elongation are continuously monitored until the sample fails. The ultimate strength is determined based on the average of six single-rib tensile tests as recommended by ASTM D6637.

Results and Discussion

Control Tests

Six fiberglass geogrid samples were tested at room temperature (20 °C ± 2 °C). Table 1 shows the ultimate tensile strength in kN/m and the ultimate strain for each sample. The results show that the ultimate strength values range between 100 and 106.8 kN/m. These values reflect the homogeneity of the tested grid sheet. The average ultimate strength for the tested samples is found to be about 104 kN/m and the corresponding strain is about 1.9%. The standard deviation of the ultimate strength and the corresponding peak strains are about 2.5 kN/m and 0.04%, respectively.

Table 1 Tensile test results under room temperature (control test)

Sample number	Ultimate strength (kN/m)	Ultimate strain (%)
1	106.8	2.0
2	103.8	2.0
3	107.5	1.9
4	102.5	1.9
5	100	1.9
6	103.8	1.9
Average	103.75	1.9

Effect of Temperature on the Stress–Strain Response

Forty-two fiberglass geogrid samples were tested under different temperatures that range from − 30 to 40 °C. Figure 4 shows the average load–strain relationships for all the tested samples. In general, the strains linearly increased with the increase in the applied loads, and the tested samples failed at about 2% strain. Compared to the results obtained at room temperature (represented by the solid line), both the material stiffness and strength increased with the decrease in temperature. Conversely, the stiffness and strength of the samples decreased as the temperature increased above 20 °C. The average load–strain relationships indicate that the ultimate strength is sensitive to temperature variations.

It is also observed that the response of the material remained linear for the range of investigated temperatures. The maximum strength value (128.5 kN/m) was measured at − 30 °C while the minimum value (98 kN/m) was obtained at 40 °C. It can be seen in Fig. 4 that both the tensile strength and stiffness decreased with the increase

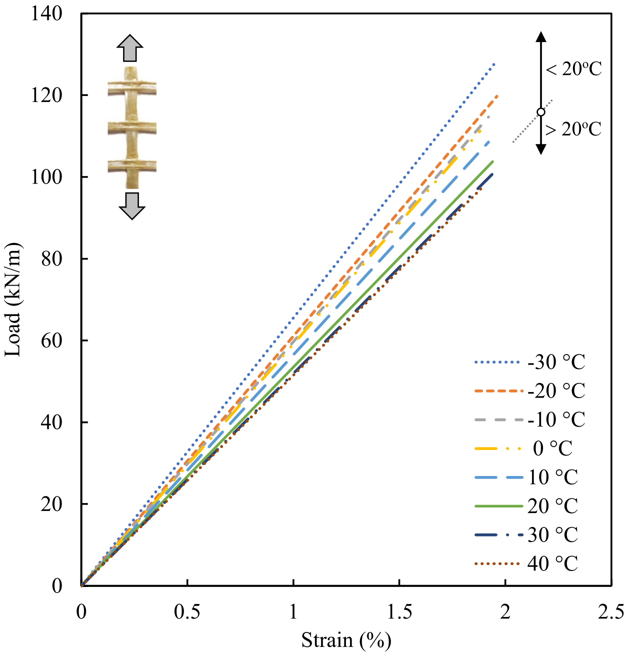


Fig. 4 The measured load–strain relationships for the investigated range of temperatures

in temperature. This confirms the temperature-dependent response of this fiberglass material.

Effect of Temperature on the Ultimate Tensile Strength

Another way of assessing the change in ultimate tensile strength of the 42 samples (6 for each applied temperature) can be achieved by plotting the average failure load for each set against the applied temperature as shown in Fig. 5. The role of temperature can be demonstrated by evaluating the rate of change in strength when temperature is raised or lowered with respect to room temperature. The decrease in strength when temperature is elevated by 20 °C (from 20 to 40 °C) is found to be about 6%. When the temperature drops from 20 to 0 °C, the material strength increased by about 7%. Further decrease in temperature from 0 to – 20 °C resulted in additional 8% increase in strength.

The above results indicate that the investigated geogrid can lose about 6% of its tensile strength when the temperature is elevated 20 °C from room temperature and can gain a similar percentage of strength when the temperature drops 20 °C above room temperature. This can be explained by the uncompromised polymer-based bond at low temperatures. As temperature increases, this bond loosens as a result of the physico-chemical properties of the geogrids. For the investigated range of temperature, the recorded change in strength is found to be relatively small and, therefore, the applied temperature did not reach the polymer's glass transition temperature that corresponds to major change in the mechanical properties of the material.

Effect of Temperature on Tensile Strains

The tensile strain at ultimate strength is usually an important design parameter, therefore, it is discussed here in a separate section. By analyzing the results of the 42 tested samples, the average strains for each data set that corresponds to a given temperature are presented in Fig. 6. The vertical axis presents the measured strains at ultimate strength normalized with respect to the corresponding strains at room temperature. For the reference case of room temperature, the average strain at ultimate was found to be 1.9% with a standard deviation of 0.05.

It is noted that some samples experienced lower ultimate strains than others regardless of ambient test temperature. However, for the investigated range of temperature, the ultimate strain did not generally exceed 2%. As no specific trend was observed for the strains at ultimate strength, the material elongation does not seem to be significantly affected by the temperature variations.

The normalized strength, which is the ratio of strength at a given temperature to the strength at room temperature, is summarized in Table 2 for each tested temperature. The first column represents the normalized strength at 0.5% strain. While the second and the third columns represent the normalized strength at 1% and 1.5% strain, respectively. At 20 °C, 30 °C, and 40 °C, the normalized strength was found to be almost constant at all measured strains. Below room temperature, however, the normalized strength increased by about 10% for all strains. As such, the material's strain seems to be more or less constant in all the tested samples. This trend is different from that observed in the ultimate strength, which was more sensitive to temperature variation.

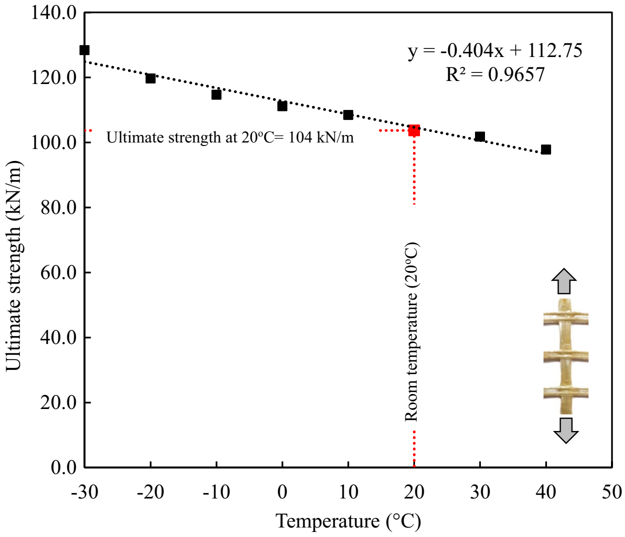


Fig. 5 The average ultimate strength at different temperatures

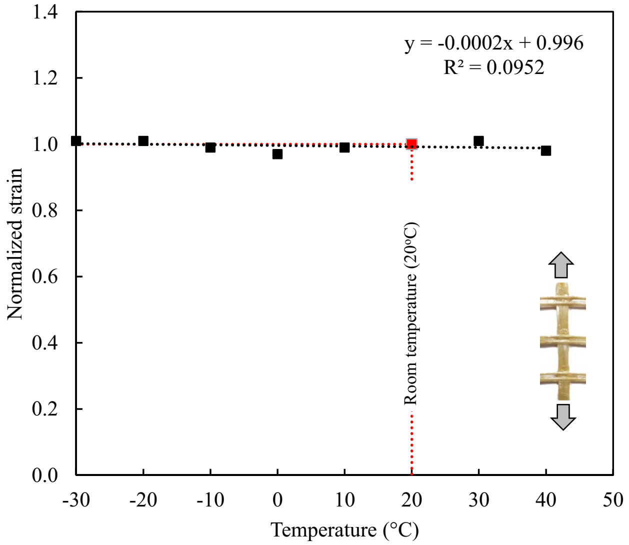


Fig. 6 Normalized strain ratios at different temperatures

Table 2 Normalized strength at different strain levels for the range of temperatures used in the tests

Testing temperature (°C)	Normalized strength at 0.5% strain	Normalized strength at 1% strain	Normalized strength at 1.5% strain
– 30	1.1	1.1	1.1
– 20	1.1	1.1	1.1
– 10	1.1	1.1	1.1
0	1.1	1.1	1.1
10	1.0	1.0	1.0
20	1.0	1.0	1.0
30	1.0	1.0	1.0
40	1.0	1.0	1.0

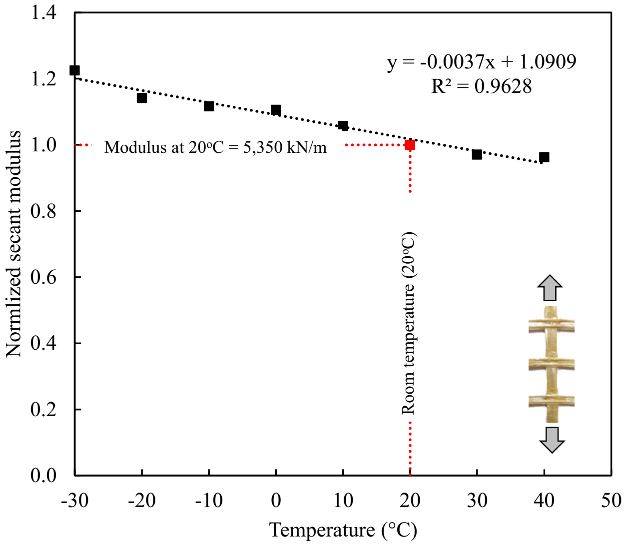


Fig. 7 The change in secant modulus at 0.5% strain for the examined range of temperature

Effect of Temperature on the Secant Modulus of Elasticity

Based on the results presented in Fig. 4, the stress–strain relationships for all tested samples are linear and samples reached failure within the elastic range. The slopes of the stress–strain lines are used here to calculate the change in modulus of elasticity due to temperature variation. The control test at room temperature provided a secant modulus of elasticity of about 5350 kN/m at 0.5% strain. When the temperature decreased from room temperature to – 30 °C, the secant modulus increased by about 23%. This indicates that the material became stiffer at low temperature, as previously noted, and became relatively ductile at higher temperature. The material's secant modulus decreased by 4% when temperature increased from 20 to 40 °C. Figure 7 shows the normalized secant modulus at 0.5% strain when temperature changed from – 30 to 40 °C. The modulus of elasticity seems to be sensitive to temperature changes. In general, the modulus of elasticity is found to change almost linearly with the change in temperature. The rate of change in the secant modulus is about 21 kN/m/°C.

Failure Modes

It is important to examine the failure patterns of the tested geogrid samples to better understand the location and the number of cracks developing as a result of the change in temperature. With the increase in ambient temperature, the ultimate tensile strength was found to decrease, and the material's failure mode was found to involve multiple cracks developing sequentially within the sample. The number and intensity of cracks was found to increase with the increase in applied temperature. Figure 8a shows a typical failure mode of one of the tested fiberglass ribs subjected to temperatures that range between 30 and 40 °C. The arrows indicate the observed locations of the cracks that, in this case, developed randomly along the sample length. It is hard, however, to precisely pinpoint an exact location of the first crack as it varies from sample to sample depending on the microstructure of the tested rib.

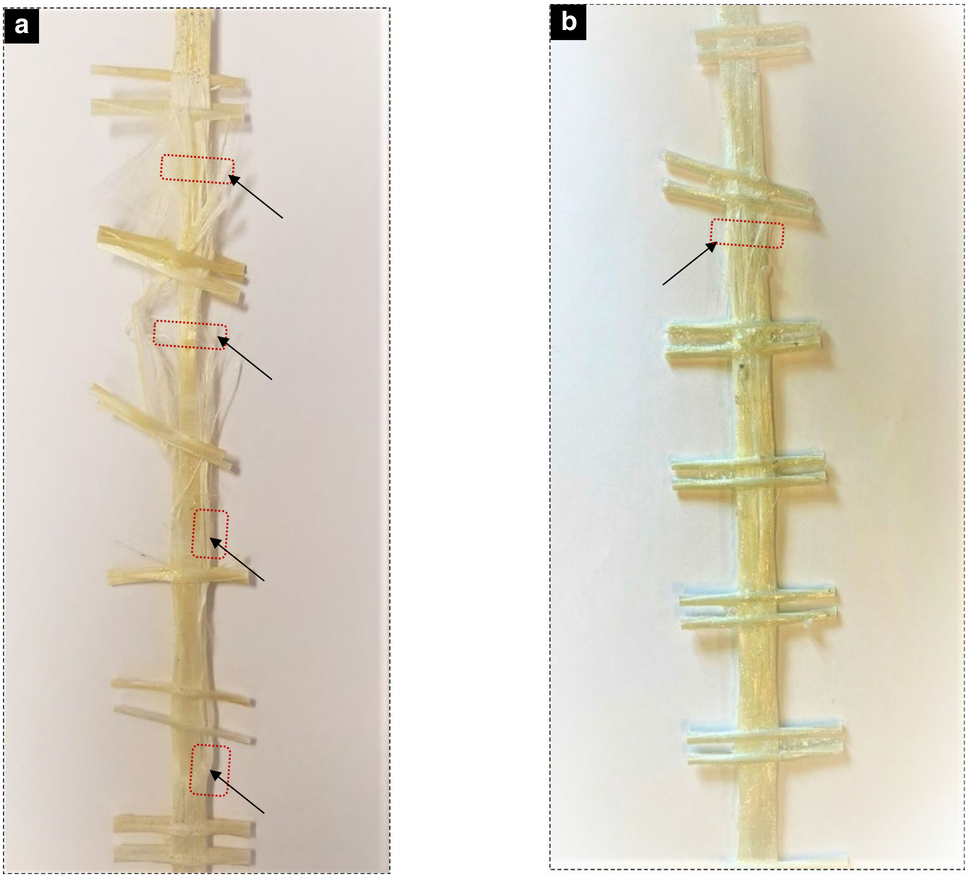
When the ambient temperature decreased from 20 to around 0 °C, cracks consistently developed at a specific location along the sample length, and the initial fracture location can be visually identified as illustrated in Fig. 8b. Another observation is the crack propagation that seems to be mostly in the longitudinal direction along the length of the sample. The overall material behavior has progressively changed from brittle at low temperature to ductile-like response at high temperatures.

Conclusions

The tensile behavior of stiff fiberglass geogrid subjected to varying temperature was investigated using a series of single-rib tests. The temperature was controlled using an environmental chamber and incrementally varied from – 30 to 40 °C. The following conclusions are made based on the experimental results:

- For these types of fiberglass geogrid material, the measured strength values at high temperatures are generally smaller than those measured at low temperatures. The tensile strength increased by about 24% as the temperature decreased to – 30 °C. In contrast, increasing the temperature to 40 °C resulted in decrease in the measured tensile strength by about 6%.
- At room temperature, the average strain at ultimate strength was found to be 1.9% and the maximum value

Fig. 8 Typical failure patterns for the cases of **a** samples tested above room temperature, **b** samples tested below room temperature



T > 20°C

T < 20°C

(Arrows point to the locations of the cracks)

did not exceed 2%. It is also observed that, for the investigated conditions, the strain is essentially insensitive to the change in temperature.

- Temperature is found to significantly affect the modulus of elasticity for this type of geogrid material. Compared with the control tests (performed at 20 °C), the samples tested at – 30 °C displayed 23% increase in the modulus of elasticity, whereas samples tested at 40 °C displayed 4% decrease in their elastic modulus.
- Failure patterns were found to be affected by the test temperature. Above room temperature, cracks are found to develop randomly along the sample length. In contrast, cracks are found to be localized at a specific location when samples are tested below room temperature.

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Author Contributions Planning and conducting experimental work: MS; editing and reviewing: MAM and SB. All authors have read and agreed to the published version of the manuscript.

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Data Availability The data that support the findings of this study are available upon request from the corresponding author.

Declarations

Conflict of interest The authors declare no conflict of interest.

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