

EFFECT OF TEMPERATURE ON TENSILE STRENGTH PROPERTIES OF GEOSYNTHETIC POLYMERIC BASE MATERIALS

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ABSTRACT

Geosynthetics made from polymeric materials are subjected to either tensile or compressive load throughout their service life in many geotechnical field applications such as reinforced slopes, retaining walls, embankments and waste containments (landfills). Temperature has important effects on tensile strength properties (i.e. ultimate tensile strength, stiffness and toughness) of polymeric geosynthetics, and hence, must properly be evaluated. It is known that polymeric materials consist of viscoelastic properties, and therefore, the degree of loss in strength of polymeric material utilized in a design is a function of temperature variation. The extent of the tensile strain depends on the magnitude of the loading as well as the type of polymer and manufacturing process from which a geosynthetic material is produced. The use of geosynthetics, if not wisely designed and deployed properly in the field (i.e. landfill side slopes), may cause stability problems and jeopardize the integrity of the infrastructure. To this end, tensile strength properties of the two polymeric materials (polyethylene, polycarbonate) from which tension elements of the most composite geosynthetic multi-layered systems are produced were measured at different temperatures ranging from 20 °C to 70 °C. The tensile tests at various temperatures were performed by using a computer automated universal testing machine insulated for the target test temperatures. The results of the experimental program will be presented along with a further discussion on the type of failure mode (i.e. tension behavior: ductile, brittle) that the polymeric specimens were followed under the application of tensile load. Additionally, a further comparison on ultimate tensile strength properties and tensile extensional (i.e. tensile strain) behavior of the two polymers prior to failure at different temperatures will be provided and the resulting impact of temperature on these tensile strength properties will be discussed. Further, the change in tension failure envelopes of both the polyethylene and the polycarbonate specimens with a change in temperature will be shown.

Keywords: Temperature effects, tensile strength, geosynthetics, polymeric materials

INTRODUCTION

Over the past few decades, the use of geosynthetics made from polymeric materials has been continuously increasing in a variety of geotechnical applications such as reinforced slopes, retaining walls, embankments, and waste containment systems. In many of these applications, geosynthetics are subjected to either tensile or compressive load throughout their service life. For example, geogrids (commonly made from highly oriented high density polyethylene: HDPE) in reinforcement applications are subjected to tensile loading. In contrast, geonets (manufactured by extruding HDPE) are exposed to compressive loading in landfill liner and cover systems (Koerner, 2005). The degree of loss in strength of these polymeric geosynthetics utilized in the design is a function of temperature variation as seasonal temperature variations influence the tensile strength properties of these geosynthetics; hence, the stability of those geotechnical applications.

BACKGROUND

Tensile strength properties of polymeric materials is an important issue in geotechnical engineering design. Geosynthetics that are made of polymers are widely used under tension in landfill side slopes in which they are subjected to constant stress throughout their service life (Koerner, 2005). To this end, many design methods utilize long-term strength or a modulus value that incorporates reduction factor to ensure the integrity of the structure and to limit deformation. Typically, the long-term strength values refer to service life from 50 to 100 years depending on the type of the engineering structure. Thus, the temperature effect on tensile strength and creep behavior of geosynthetics must be properly evaluated (Nielsen, 1974) in detail so that the appropriate factor of safety, (FS) can be incorporated into the long-term design of structural systems.

Geosynthetics produced from polymer resins consist of viscoelastic properties. Under an increase in ambient temperature, geosynthetics can exhibit creep strain which may potentially cause damage to

the corresponding infrastructural system (i.e. landfill). The extent of the creep strain/deformation depends on the magnitude of the temperature change as well as the type of polymer and manufacturing process of the geosynthetics. As such, the creep mechanism of polymeric materials is governed not only by load but also temperature (Findley, 1960; Roylance, 2001). To this end, temperature has a significant effect on the mechanical properties of polymers, such as modulus, tensile strength, and hardness (Fig. 1). Polymeric materials soften and eventually flow as they are heated. Therefore, it is important to know the limiting temperatures at which polymer components can still be loaded with moderate deformations.

Further, the tensile behavior of a polymer is strongly related to the state of the material which is dependent on its temperature. Polymers (i.e. Oriented Crystal Fiber, Glassy) are brittle at the lowest temperatures. As the temperature increases, they become more “tough”, until they reach brittle-ductile transition above which polymers become sufficiently ductile so that they can exhibit necking behavior (Fig. 1). Further increases in temperature may lead to a rubber-like behavior as illustrated in Figure 1; however, which is out of context of this research study. Moreover, it should be noted that the type of behavior a polymeric material shows (i.e. brittle versus ductile) when tested under tension depends on the strain rate of extension in tensile tests (Nielsen and Landel, 1994; Dowling 2007). For example, if extremely high strain rates are used, a polymer can exhibit brittle behavior at almost any temperature.

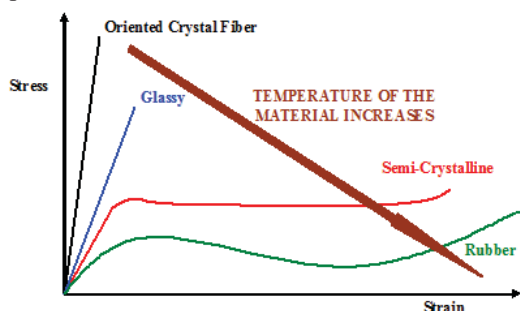


Fig. 1 Typical tensile test graphs of four different state polymers tested to failure: The state of polymer is primarily related to its temperature (Daniels, 1989)

EXPERIMENTAL WORK

Materials Tested

In order to study tensile behavior and the developed stress–strain response of polyethylene and polycarbonate specimens at different temperatures, a

set of laboratory tests were performed by measuring thermo-mechanical properties of the aforementioned polymeric materials using a universal testing machine in controlled force/strain rate mode. Polyethylene and polycarbonate specimens were stretched under tension and ruptured using a constant-rate-of extension (CRE) type tensile test at a gage length (i.e. initial sample length) of 130 mm at different elevated temperature conditions. The details on the dimensions of polyethylene and/or polycarbonate dogbone specimens are shown in Fig. 2.

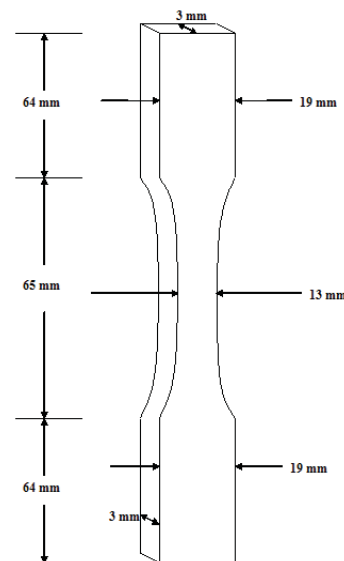


Fig. 2 Schematic showing the dimensions of Polyethylene and Polycarbonate dogbone test specimens

Polyethylene

Polyethylene is one of common base polymer types from which geosynthetics are made. It is generally used to produce geosynthetic tension elements of infrastructural systems including geomembranes, geogrids and geonets find widespread use in common geotechnical applications (i.e. landfills). Polyethylene (PE) is a polymer consisting of long chains of the monomer ethylene. The ethylene molecule is chemically represented as C_2H_4 for which two CH_2 groups are connected by a double bond ($CH_2=CH_2$). Polyethylene is created through polymerization of the ethylene molecules. It is produced through either radical polymerization, anionic addition polymerization, ion coordination polymerization or cationic addition polymerization (Osswald and Menges, 1995). The molecular chemical structure of ethylene which is the building stone of polyethylene as well as the repeating unit of polymeric chain of polyethylene is shown in Fig. 3.

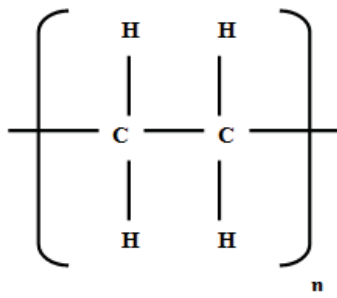


Fig. 3 Schematic representation of the repeating unit of Polyethylene; C–H bond angles are not 90° as this diagram indicate, but are approximately 110°, as each carbon atom is tetrahedral (Osswald and Menges, 1995)

Polycarbonate

Polycarbonates that can easily be worked, molded, and thermoformed are a particular group of thermoplastic polymers. They are classified between commodity plastics and engineering plastics because of their enhanced physical features such as relatively enhanced temperature resistance, impact resistance and optical properties. The name polycarbonates indicates that they are polymers having functional groups linked together by carbonate groups (-O-(C=O)-O-) (Daniels, 1989) in a long molecular chain as shown in Fig. 4.

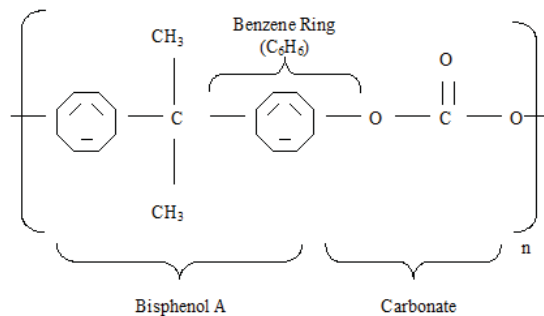


Fig. 4 Schematic of extended chemical structure of Polycarbonate molecules (Osswald and Menges, 1995)

Testing Equipment and Instruments

The tension behavior and material properties of polyethylene and polycarbonate specimens at different temperatures under tensile load were measured using a universal testing machine with grips controlled by a computer for load control, strain measurement and insulated for the target test temperatures ranging from 20 °C to 70 °C.

Universal testing machine load frame

The universal testing machine load frame is a rigid support structure into which specimen of the material tested is installed. The specimen is secured using grips, one on the load frame base (i.e. bottom side of specimen), and one on the crosshead (i.e. top side of specimen). There is a load cell which is mounted between the crosshead and the crosshead grip. The vertical movement of load frame leading either tension or compression load on specimen is controlled by the software according to user specifications. When test begins, the controller software sends a signal to the load frame to drive the crosshead in a specified direction at a specified speed. As the crosshead moves up or down, the specimen is stretched or crushed while the load cell measures the force applied to the specimen. In return, the changes in load and dimension are sent back to the controller software for data storage and current test status analysis. The load frame contains several electronic boards, which control communication between the software and the load frame. It also has two limit switches that are set to prevent the crosshead from traveling too far in either direction.

Controller software

The controller software enables the user to access measurement instrumentation readings as well as to determine the test specimen current stress-strain state. Controller program user interface enables user interaction directly to the test process (i.e. tensile load/extension progress). In order to proceed through different test tasks, the operational buttons on the main interface can be selected leading to subsequent test phases.

Testing method

The tensile strength properties of two different polymeric materials (polyethylene, polycarbonate) were evaluated by applying tensile (i.e. extensional tension) load at a constant strain rate of 1.5 mm/min. during elastic elongation of both tested material; at a constant strain rate of 50 mm/min. and 12.5 mm/min. throughout the inelastic deformation of polyethylene and polycarbonate specimens, respectively. These strain rates were chosen in order to observe the entire tensile deformation/extension behavior of the tested materials during elastic elongation and plastic deformation phases under tensile load until the failure/rupture takes place. As such, the entire tensile extension behavior for the tested polymers consisted of elastic elongation and inelastic deformation under load as well as constant strain rate until the rupture of the test specimens occur.

TEST RESULTS

Tension Curves at Different Temperatures

Polyethylenes

Figure 5 illustrates the uniaxial force-elongation behavior for polyethylene specimens under a “constant rate” of extension loading. The force-displacement curves underwent a relatively short elastic deformation stage compared with a longer plastic deformation phase. In other words, polyethylene specimens experienced larger strains prior to failure by progressing through all three main phases of elasto-plastic deformation. The tensile stress – strain behavior for the tensile tests at different temperatures performed on the polyethylene specimens show that the plastic elongation initiates at axial strains of ~15% at lower test temperatures and at axial strains of ~20% at higher test temperatures. As such, the total strain to plastic deformation (i.e. strain for the onset of plastic elongation or unrecoverable deformation) increases with increased ambient temperature.

For development and shape of the tension curves at different temperatures, the tensile stress increases with increasing axial strain, then, it remains almost constant during inelastic deformation of the polyethylene specimens. The inelastic portions of the stress-strain curves at different temperatures were essentially parallel to the horizontal axis. The general pattern in tension tests for polyethylenes is the same: sharp increase to a local maximum, steady rise at a reduced slope, then leveling off at higher strain levels. As such, the tensile stress increases very rapidly within axial strain of 4–8%, then, it undergoes through the transition zone with a steady rise at a reduced slope before reaching plastic deformation at axial strain rate of >15%. Further, the tested polyethylene specimens underwent the failure mode of ductile tension behavior under the application of tensile load regardless of test temperature ranging from 20 °C to 70 °C (Fig. 5).

In principle, the tensile stress – strain behavior shown in Fig. 5 can be divided into three separate zones, depending on the molecular response of the polymer to the level of applied strain (Stein and Powers, 2006; Dowling, 2007): i) Within Zone I, the response to load is instantaneous and elastic, since the deformations are recoverable upon load removal; ii) Deformations within Zone II are still recoverable, but not instantaneously. Time dependent response within Zone II usually is generally associated with visco-elastic behavior; iii) Within Zone III, the material exhibits an inelastic response in that the deformations are irrecoverable upon load removal and response within this region is related to visco-plastic behavior in which strains consist of visco-elastic as well as plastic components. In terms of

physico-chemical considerations, the stretching of inter-atomic bonds occurs in Zone I when going through elastic elongation. Throughout the transition zone (Zone II), polymer molecular chains get straightened. Lastly, the relative displacement of molecules in the polymer takes place in Zone III during plastic deformation.

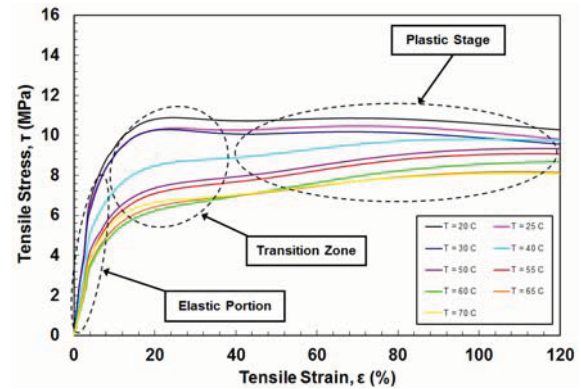


Fig. 5 Tensile stress versus strain curves for polyethylene specimens tested at different temperatures

Figure 6 shows close-up view of tensile stress – strain curves for the polyethylene specimens tested at various temperatures. The polyethylene tension failure envelope diminished as temperature increased. The tension curves from the tests at higher temperatures fall within the envelope of the tension curves from the tests at lower test temperatures.

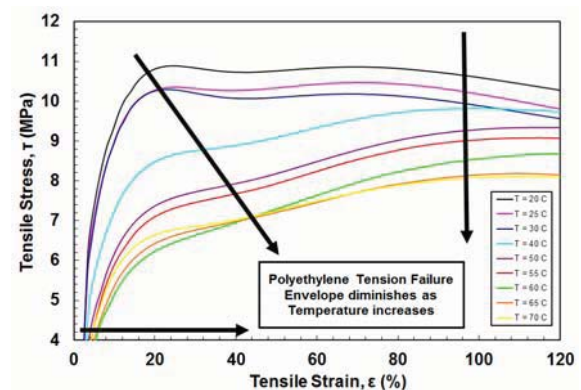


Fig. 6 Tensile stress–strain curves at different temperatures (polyethylene) [close up view]

The plastic-extension dominant tensile stress – strain behavior (Fig. 5) of the polyethylene tested over a temperature ranging from 20 °C to 70 °C indicates that the polyethylene initially behaves as relatively more solid-like in its strength properties during elastic stage of tensioning, and then, changes to plastic rubber-like straining (i.e. tensional extension) at greater extensional displacements.

Finally, the mobilized ultimate tensile strength decreases slightly through the end of the tests with the result that the polymeric material can no longer hold its own shape, and thus, the rupture/break develops and the material fails.

Polycarbonates

The tensile stress – strain behavior of the polycarbonate specimens measured at various test temperatures are shown in Fig. 7. The shape of stress-strain curves of the polycarbonate specimens at different temperatures were in good agreement and the influence of temperature on the tensile strength properties of this polymeric material (polycarbonate) was lesser as compared to the effect of temperature on the tensile strength properties of the polyethylenes tested for the same test temperature range (20 ° C – 70 ° C). This is due to improved thermo-physical properties of the polycarbonates such as enhanced temperature resistance and better impact resistance.

The tension curves from different tensile tests performed at various elevated temperatures indicate that plastic elongation occurs in the tension tests of polycarbonates prior to failure of the specimens. The tensile stress increases rapidly with increasing axial strain within only a relatively small amount of strain (3%), then, the tensile stress remains almost constant during inelastic deformation of this polymeric material after a total strain of ~6%. The inelastic portions of the stress-strain curves are essentially parallel to each other (Fig. 7).

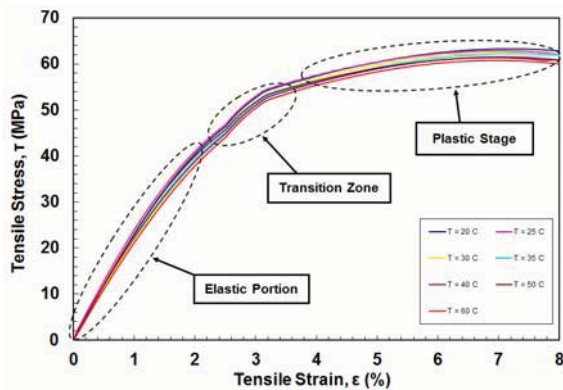


Fig. 7 Tensile stress versus strain curves for polycarbonate specimens tested at different temperatures

As seen in Fig. 7, the general pattern in the extensional constant strain rate tension tests of polycarbonates at different temperatures is the same: i) sharp increase to a local maximum (the tensile force increases rapidly within relatively small axial strains: <3-4%); ii) steady rise at a reduced slope (continues through the transition zone before

reaching plastic deformation); then, iii) leveling off at higher strain levels (remains almost constant throughout plastic deformation until failure). As such, tensile stress – axial strain curves of the polycarbonate specimens tested in the temperature range from 20 °C to 70 °C gave a similar form with a sharp increase prior to arriving transition zone, then, experiencing plastic deformation. Similar to the polyethylene, the polycarbonate tension failure envelope diminished as the test temperature increased. As such, the tensile stress – axial strain envelope of the tensile tests at higher temperatures fall within the stress-strain space of the tensile tests at lower temperatures (Fig. 8).

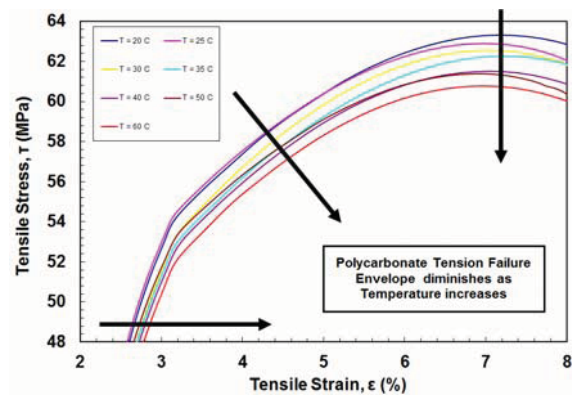


Fig. 8 Tensile stress–strain curves at different temperatures (polycarbonate) [close up view]

Both polyethylene and polycarbonate specimens underwent the same failure mode over the entire test temperature range (20 °C – 70 °C) that they followed ductile tension behavior under the application of tensile load. Polyethylene specimens experienced higher strains prior to failure than polycarbonate specimens as a consequence of their chemical structure and the nature of bonding between molecules (Figs 5 and 7). Additionally, the stress-strain curves from the polyethylene tests falls within the failure envelope of that defined by the polycarbonate tests. In light of this, it can be noted that the polycarbonates is relatively brittle than the polyethylenes. As such, the resulting tensile stress–strain curves of polycarbonate tests located on the upper part of the stress-strain space as compared to the stress-strain curves of the polyethylene tests. Comparing the resulting tensile stress – axial strain behavior of polyethylene and polycarbonate specimens, the polycarbonates are much stronger and stiffer than the polyethylenes under tensile load (i.e. extensional tension) application in the test temperature range (20 °C – 70 °C).

Tensile Strength and Temperature

Using the resulting tensile stress – axial strain curves (i.e. force – extension/elongation curves) at different temperatures, the tensile strength engineering properties of polyethylene and polycarbonate specimens including tensile strength (τ_{MAX}) and modulus of elasticity (E) were evaluated and determined for different elevated temperature conditions ranging from 20 °C to 70 °C that is typical range of high temperatures experienced by the geosynthetic materials utilized in common geotechnical field applications (i.e. landfills) for which the geosynthetic tension elements of these infrastructural projects are exposed to the temperature variations generally at this test temperature range (20 °C – 70 °C) in the field.

One of the most important mechanical properties of polymeric materials is its tensile strength under extensional force at different ambient conditions such as temperature that shows the toughness, indestructibility and long-term durability of the polymeric geosynthetic material employed in the geotechnical infrastructure applications. In light of the tensile test results performed at different ambient temperatures, the geosynthetic materials produced using either type of polymer (i.e. polyethylene, polycarbonate) as a base material do not retain their tensile strength and toughness properties as temperature changes.

Polyethylenes

It was observed as a result of thermo-mechanical tensile tests performed at different temperatures on the polyethylene specimens that the tensile strength, (τ_{MAX}) decreased with temperature with lower strength values measured at higher elevated temperatures (Fig. 9). The polyethylene specimens tested at room temperature conditions (i.e. lowest test temperature) exhibited the largest toughness under extensional tensile force and resulted in the largest tensile strength value attained. Therefore, it is noted that polyethylenes are more resistant to tension at lower temperatures (i.e. 20 °C), but becomes weaker at higher elevated temperatures (i.e. 70 °C). Further, Fig. 9 shows that the polyethylene ultimate tensile strength decreased at an increasing rate with temperature. In light of this resulting trend observed from the experimental data, it can be noted that the influence of temperature on the polyethylene, and thus, on the geosynthetic materials produced from polyethylene base material and employed as tension members of geotechnical field applications can be more critical for especially higher elevated temperature conditions particularly above 70 °C.

Several different types of regression analyses such as linear, exponential, logarithmic were

performed on the thermo-mechanical tensile test data. The 2nd order polynomial regression provided the best correlation between tensile strength and temperature such that a very good fit between intermittent test data and continuous regression curve for which a higher coefficient of determination (CoD) of 0.9878 was obtained as compared with that of linear, exponential or logarithmic regression methods which gave lower CoD values.

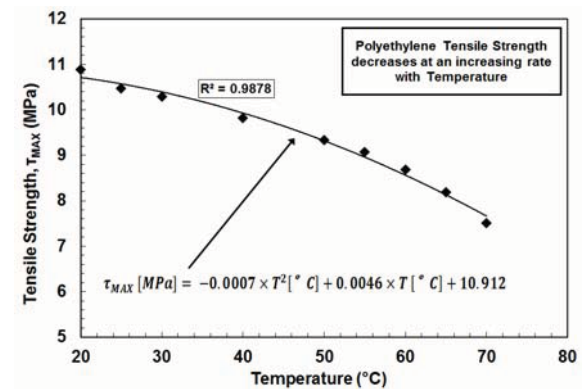


Fig. 9 Tensile strength and temperature (polyethylenes)

The empirical relationship (Equation 1) developed through regression analysis of tensile test data between strength and temperature can be utilized to relate the change in tensile strength to the variation in temperature as follows:

$$\tau_{MAX} [MPa] = -0.0007 \times T^2 [^{\circ}C] + 0.0046 \times T [^{\circ}C] + 10.912 \quad (1)$$

where:

τ_{MAX} = Ultimate Tensile Strength in MPa

T = Temperature in °C

It is evident from the test results that there is an inverse proportion in between tensile strength and temperature in which they possess higher strength values at lower temperatures due to more intact chemical composition and stronger bonding type of polyethylene polymer molecules at cooler temperatures resulting from the material physico-chemical properties. An increasingly diminishing behavior in which the rate of decrease gets larger with increasing temperature was observed for the tensile strength and temperature relationship of the polyethylene specimens tested at various different temperatures ranging from 20 °C to 70 °C.

Polycarbonates

The change in tensile strength of polycarbonates with temperature is presented in Fig. 10. Polycarbonate tensile strength decreased at a

logarithmic rate with increasing temperature for the test temperatures ranging from 20 °C to 70 °C. Regardless of ambient test temperature, the resulting tensile strength values obtained from tensile tests of the polycarbonate specimens were greater than those obtained from the polyethylene tests due to chemical composition, and hence, stronger bonding type of polycarbonate polymer molecules.

In light of the tensile test results, the mechanical properties, in particular ultimate tensile strength (τ_{MAX}) of polycarbonates, do not remain the same within the range of test temperatures (20 °C – 70 °C) typically experienced by polymeric geosynthetics utilized in widespread geotechnical infrastructure applications (i.e. landfills). However, it should further be noted that polycarbonates are less influenced by the change in ambient temperature as compared to polyethylenes based on the results of thermo-tensile tests on the polycarbonate specimens which showed that the ultimate tensile strength for the polycarbonates decreased slightly (i.e. only 3-4%) with an increase in the temperature from 20 °C up to 70 °C.

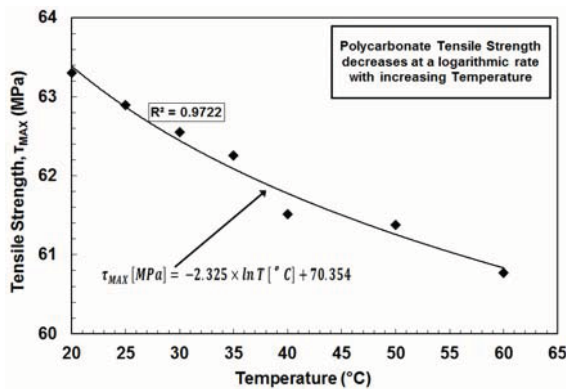


Fig. 10 Tensile strength and temperature (polycarbonates)

As seen in Figure 10, a logarithmic decremental behavior with a reduced rate of decrease at higher elevated temperatures, particularly above 40 °C, was observed in tensile strength versus temperature relationship of polycarbonates. Several different regression analyses including linear, exponential and polynomial were applied to the measured tensile strengths at the various ambient temperature levels. A natural logarithmic regression analysis provided the best correlation between the discontinuous test data and continuous regression curve with a high coefficient of determination (CoD = 0.9722). For polycarbonates that were constant strain rate tensile tested under extensional force at various elevated temperatures, the equation relating the tensile strength to the temperature change is given in Equation 2 as follows:

$$\tau_{MAX} [MPa] = -2.325 \times \ln T [°C] + 7 \quad (2)$$

where:

τ_{MAX} = Ultimate Tensile Strength in MPa

T = Temperature in °C

Stiffness (Elasticity Modulus) and Temperature

The modulus of elasticity (i.e. Young's modulus, E) for the tested polymeric materials (polyethylene, polycarbonates) were computed using the resulting tensile stress versus axial strain curves obtained at different temperatures from the tensile tests of polyethylene and polycarbonate specimens. The slope of initial linear portion of the stress-strain curves was used to determine the elasticity modulus as shown in Fig. 11.

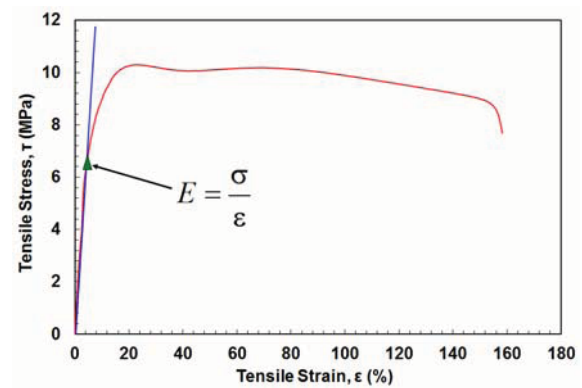


Fig. 11 The Computation and determination of elasticity modulus from tensile stress-axial strain curves

The linear elastic portion of the tensile stress – axial strain curves rotates clockwise as ambient test temperature increases demonstrating a reduction in the material stiffness with temperature. Therefore, it is evidently seen from the tensile test results at different temperatures that both the polyethylene and the polycarbonate modulus of elasticity is inversely proportional to temperature. The maximum stiffness for all the tensile tests performed in this study was obtained at the lowest test temperature (room temperature, 20 °C). At higher temperatures, the tested specimens underwent larger deformations before proceeding to the occurrence of yielding or transition deformation from elastic to plastic elongation. Additionally, as indicated previously, the tensile strength values attained at lower temperatures were greater than those attained at higher temperatures for both the tested polymer type due to polymeric material inherent physical properties which changes with a change in temperature, and thus, the bonding strength between molecules of both polymers.

Polyethylenes

The relationship between stiffness (i.e. modulus) and temperature for the polyethylenes is presented in Fig. 12. Polyethylene elasticity modulus decreased exponentially with increasing temperature. The resulting exponential decaying regression analysis provided the best correlation between Young's modulus (*E*) and temperature with a relatively high coefficient of determination (CoD = 0.9783) compared to that of the other regression methods.

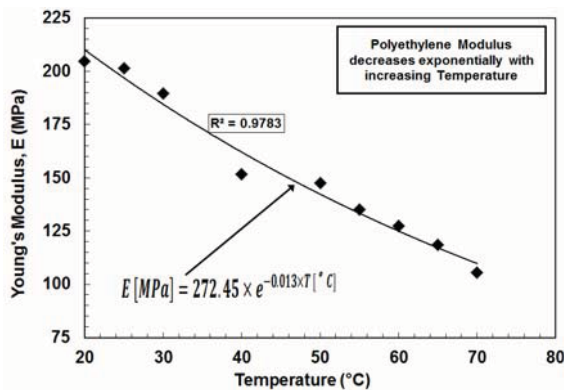


Fig. 12 Modulus of elasticity and temperature (polyethylenes)

The empirical relationship between elasticity modulus (Young's modulus) and temperature was developed based on the results of tensile tests performed on the polyethylene specimens at different temperatures and could be utilized as a mathematical equation to relate elasticity modulus to temperature change in which Young's modulus values follow an exponential pattern with increasing temperature as presented in Equation 3:

$$E [MPa] = 272.45 \times e^{-0.013T} \quad (3)$$

where:

E = Elasticity Modulus in MPa

T = Temperature in °C

Polycarbonates

The results of thermo-tensile tests on the polycarbonate specimens showed that the modulus of elasticity (i.e. stiffness) decreased at a decreasing rate (i.e. particularly above 40 °C) with temperature. As such, the initial elastic modulus was the largest at the lowest test temperature (room temperature, 20 °C). Figure 13 shows the change of elasticity modulus (Young's modulus, *E*) as a function of temperature. The polycarbonate specimens were stiffer and firmer at lower temperatures and became relaxed and more flexible at higher elevated temperatures.

Further, it is evident from the tensile test results

at different temperatures ranging from 20 °C to 70 °C that polycarbonates, regardless of ambient test temperature, are much stiffer than polyethylenes as the modulus values obtained from polycarbonate tension tests were approximately ten times greater than that of the stiffness values attained in the tests from polyethylene specimens. Additionally, the relative (i.e. percentage) decrease/change in the magnitude of modulus with respect to the base values measured at the lowest test temperature (room temperature, 20 °C) was lesser for the polycarbonates compared to the relative decrease/change in the magnitude of modulus with increasing temperature with respect to room temperature conditions for the polyethylenes.

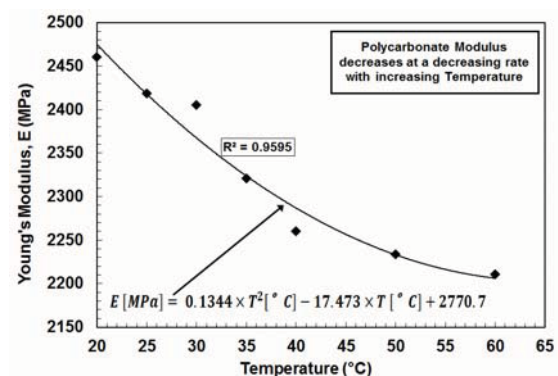


Fig. 13 Modulus of elasticity and temperature (polycarbonates)

As seen in Fig. 13, a variably decreasing trend in the value of modulus with increasing temperature, in particular above 35 °C, was observed from the resulting trend of test data. This resulted in attaining a 2nd order polynomial trend/behavior between modulus and temperature for polycarbonates for which the elasticity modulus decreases at a decreasing rate with increasing temperature.

The polynomial regression analysis performed on the data exhibited a good fit between intermittent test results and continuous regression curve with a relatively high coefficient of determination, (CoD = 0.9595). The closeness of fit between the regression and test data indicates that there occurs a good correlation between the temperature and the modulus of the polycarbonates.

The developed empirical equation (i.e. analytical and closed form) showing the relation between elasticity modulus (Young's modulus) and temperature is given in Eq. 4:

$$E [MPa] = 0.1344 \times T^2 [^{\circ}C] - 17.473 \times T [^{\circ}C] + 2770.7 \quad (4)$$

where:

E = Elasticity Modulus in MPa

T = Temperature in °C

DISCUSSIONS AND COMPARATIVE ANALYSES ON THE RESULTS

The shapes of stress-strain curves for all the tests performed on polyethylene and polycarbonate specimens at various temperatures were in good agreement and indicated that plastic elongation behavior occurs in the polyethylenes and the polycarbonates under tensile load prior to failure. In the tests, the tensile stress increases with increasing axial strain, then, it remains almost constant during inelastic deformation of the two polymeric materials after passing through yielding deformation at all temperatures tested. The tension curves are dominantly exhibiting a nonlinear pattern with a gradual decrease in inclination of initial linear slope as temperature increases indicating lower initial stiffness or modulus at higher elevated temperatures. Further, the inelastic portions of the stress-strain curves are essentially parallel. It is noted that polymeric materials typically exhibit nonlinear stress-strain behavior as stress relaxation occurs throughout loading. The observed force-extension behavior of the two tested polymers indicated that they became stronger and stiffer as temperature decreased under tensile load application. The elastic portion of tensile stress – axial strain curve rotated “clockwise” demonstrating the reduction in stiffness; hence, modulus with increasing temperature.

Polyethylenes experienced larger axial strains than polycarbonates prior to failure. Brittle and/or instantaneous tension rupture for both polymer types was not observed for the temperature range tested (20 °C – 70 °C). It is noted that brittle failure modes generally occur under glass transition temperature (T_g) of the polymeric materials as the nature of bonding between the molecules of both the polyethylenes and the polycarbonates are based on ambient temperature.

It was observed from the test results that polycarbonate specimens broke at lower strain levels, while, the polyethylenes possessed high level of extension and greater strains. As such, the tested polyethylene was highly ductile with the majority of the specimens experiencing a large amount of plastic deformation before rupture. For example, regardless of test temperature, polyethylenes were able to extend up to a maximum strain of more than 120% which results in a high energy absorption level. There is an apparent trend observed in the tensile stress – axial strain failure envelopes for both the polymeric materials that the stress-strain curves diminished as the ambient temperature increased. This variation in tension versus extension behavior shows the influence of temperature on force-displacement response of the polyethylenes and the polycarbonates. As such, all of the tension curves at different temperatures follow very similar pattern with an initial increase and thereafter a non-linear

behavior; however, both the polyethylene and polycarbonate tension failure envelopes diminish and the size of area under the curve shrinks as ambient test temperature increases. In other words, for the two tested polymers, the tensile stress – axial strain curves from higher elevated temperature tests fall within the failure envelope of that defined by the room temperature test.

Both the polyethylenes and the polycarbonates exhibited temperature dependent “stiffness” and “ductile elasto – plastic” tensile behavior in the temperature range tested (20 °C – 70 °C). As such, the polyethylene specimens as well as the polycarbonate specimens exhibited nonlinear elasto – perfectly plastic tension behavior under extensional force at all temperatures tested. The tensile strength was the largest at room temperature and decreased with increasing temperature. Polycarbonates are much stiffer than polyethylenes for which the modulus values were ten times smaller than those of polycarbonates at all test temperatures ranging from 20 °C to 70 °C.

CONCLUSIONS

The experimental study presented in the paper was conducted to evaluate temperature effects on tensile strength properties of the two polymeric materials (polyethylene, polycarbonate) used as a core/base materials to produce geosynthetics. The major impacts of temperature on tensile strength properties of both the tested polymeric materials were the decrease in ultimate tensile strength and reduction in stiffness that resulted in loss of toughness. In light of this, it is noted that the degree of loss in tensile strength properties of polymeric geosynthetics utilized in design is a function of temperature variation. Therefore, poor estimates of temperature effects on polymeric geosynthetics can lead to under-design issues that can jeopardize the safety of the construction and/or the infrastructure.

The following conclusions of this research study are drawn as a result of experimental findings from the tensile tests at different temperatures on polyethylene and polycarbonate specimens:

- The tensile tests resulted in a similar trend of tension load-elongation response at all test temperatures such that the tensile stress – axial strain curves at different temperatures have a nonlinear elasto-perfectly plastic form in terms of stress-strain relationship. Both polyethylene and polycarbonate specimens underwent the same failure mode that they followed ductile tension behavior under the application of tensile load.
- Polyethylene specimens experienced larger extensional strains prior to rupture/failure than

polycarbonate specimens over the entire temperature range tested (20 ° C – 70 ° C).

- The resulting tensile stress – axial strain curves for lower temperature tests are located on the upper part of the stress-strain space as compared to tensile stress – axial strain curves of higher elevated temperature tests such that the tension failure envelope for both the tested polyethylene and the polycarbonate specimens diminished as the temperature increased.
- The tensile strength values obtained at lower temperature tests for both polyethylenes and polycarbonates were higher than those obtained at higher elevated temperature tests.
- Temperature has a significant effect on the modulus of the two tested polymers. The values of Young's modulus for both the polyethylenes and the polycarbonates decreased with increasing temperature such that they were stiffer at cooler temperatures than being at higher elevated temperatures.
- The tensile strength values obtained from the polycarbonate tests were greater than those obtained from polyethylene tests due to improved chemical composition and stronger bonding type of polycarbonate molecules as compared to that of polyethylenes.
- Regardless of test temperature, polycarbonate specimens were much stiffer than polyethylenes as the modulus values obtained from polycarbonate tension tests were approximately ten times bigger than that of polyethylene tests.

As a closing remark, it is noted that the test results can vary greatly for the same polymer depending on boundary conditions and sample configuration as a consequence of the diversity of

chain and molecular structure found within the broad range of polymers (Nielsen and Landel, 1994; and Dowling, 2007).

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