MECHANICAL CHARACTERIZATION TESTING OF THERMOPLASTICS AND COMPOSITE MATERIALS

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Polymers and Composite Materials

Polymer materials in their basic form exhibit a range of characteristics and behavior from elastic solid to a viscous liquid. These behavior and properties depend on their material constituents, their structure, temperature, frequency and time scale at which the material or the engineering component is analyzed. The viscous liquid polymer is defined as by having no definite shape and flow. Deformation under the effect of applied load is irreversible. Elastic materials such as steels and aluminum deform instantaneously under the application of load and return to the original state upon the removal of load, provided the applied load is within the yield limits of the material. An elastic solid polymer is characterized by having a definite shape that deforms under external forces, storing this deformation energy and giving it back upon the removal of applied load.

Thermoplastic polymer resins consist of long polymer molecules which may or may not have side chains attached to them. The side chains are not linked to other polymer molecules as shown in Figure(1). Thus there is an absence of cross-links in the thermo- plastic structure. Thermoplastic resins in a granular form can be repeatedly melted or solidified by heating and cooling. Heat softens or melts the material so that it can be molded. Cooling in the mold solidifies the material into a given shape. There are two types of thermoplastic polymers, Crystalline and Amorphous. Following list enumerates the features and properties of both the polymer types.

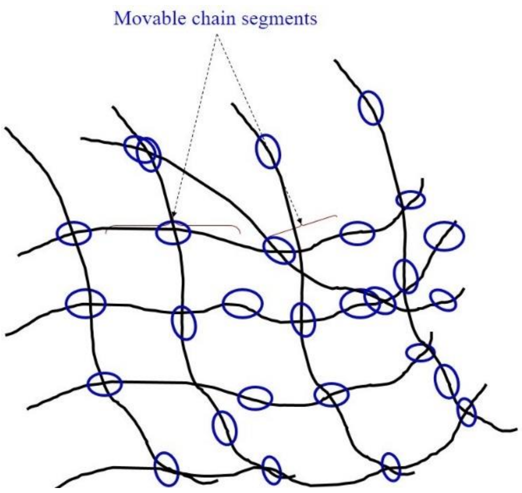


Figure 1: Chains in Thermoplastic Polymers

Crystalline Polymers:

1. Crystalline solids break along particular points and directions.
2. Crystalline solids have an ordered structural pattern of molecular chains.
3. Crystalline solids flow well at a higher temperature.
4. Reinforcement with fibers in crystalline polymers increases the load-bearing capabilities.
5. Crystalline polymers tend to shrink more than amorphous.
6. The molecular structure of crystalline polymers makes them more suitable for opaque parts and components.
7. Examples: Polyethylene, Polypropylene, Nylon, Acetal, Polyethersulfone, etc.

Amorphous Polymers:

1. Amorphous solids break into uneven parts with ragged edges.
2. Amorphous solids have a random orientation of molecules with no proper geometrical or pattern formation.
3. Amorphous solids do not flow as easily and can give problems in mold filling.
4. Examples: ABS, Polystyrene, Polycarbonate, etc.

Figure (2) shows the general types and classification of polymers.

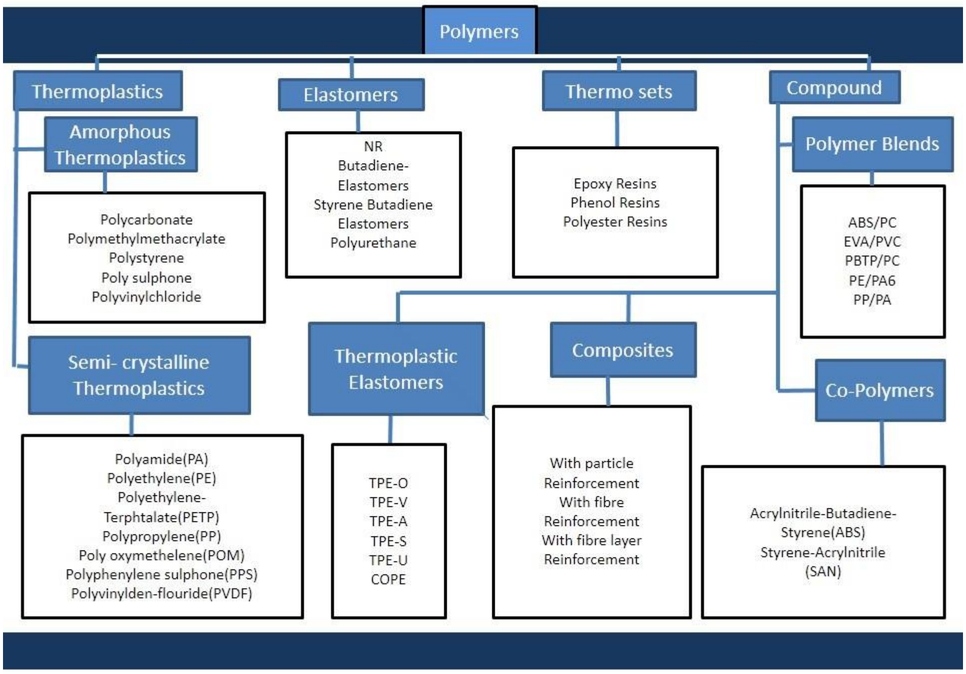
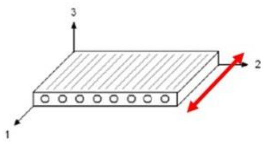


Figure 2: Types of Polymers and Their Classification

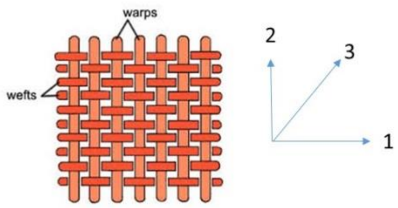
The need to improve the mechanical properties of polymers drives the development of various composites. Composites express a mechanical behavior significantly different from that of conventional materials. They provide high load carrying capability, high stiffness to weight ratio and tolerance to damage from water, specific industrial oils, greases etc.

Composite materials are engineered or naturally occurring materials made from two or more constituent materials. The properties of the constituent materials are mostly significantly different. The physical, mechanical and chemical properties remain separate and distinct within the finished material structure. Most composites are made with stiff and tough fibres in a polymer matrix. The polymer matrix is weaker and acts more as a binder and parent material. The objective is usually to come up with a material structure which is strong and stiff able to carry heavy loads. Commercial grade composite materials mostly have glass or carbon fibres in a matrix of thermosetting polymers like epoxy, nylons and polyester based resins. Glass fibres are the most frequently used reinforcing fibres in reinforced polymers. The mechanical characteristics which are predominantly improved by these fibres are tensile and compressive strength. In addition, thermal dimensional stability also increases. Thermoplastic polymers are preferred as the matrix material where the end goal is to make moldable parts and components. Glass filled nylon and other polymers offer good mechanical, chemical at a lower cost. Fibre-Reinforced Polymer (FRP), is a composite material made of a polymer matrix reinforced with fibres. These fibres are usually glass or fibres. FRPs are commonly used in the aerospace, automotive, marine, and construction industries.

Composite materials also employ continuous fiber reinforcements in the form of a ply. Figure 3 shows two types of such plies where unidirectional fibers and woven fabric bundles are laid out. These plies are impregnated by a polymer resin to form a ply structure. For most composites, the ply is the basic building block as a lamina structure. This lamina may be a unidirectional prepreg, a fabric, or a strand mat.



Unidirection Ply in a Composite Specimen



Woven Fabric Composite showing Warp and Weft

Figure 3: Unidirection and Woven Fabric Composites

Mechanical and Physical Testing:

The mechanical and physical testing of polymers and their composites is important to determine the material properties. These properties help us understand the deformation characteristics and failure modes which can further be used in design and analysis of end products. The mechanical and physical testing ensure that material complies with performance requirements in accordance with industrial specifications, especially to the demanding aerospace, automotive, consumer, medical industries. Mechanical testing of polymeric composites involves the determination of mechanical parameters such as strength, stiffness, elongation, fatigue life etc., to facilitate its use in the design of structures.

The mechanical testing of composite materials involves a range of test types and standards like ASTM, ISO, EN etc., along with testing conditions in different environments.

The most common mechanical properties such as Modulus of Elasticity, Poisson’s ratio, Tensile strength, and Ultimate tensile strain for composites are obtained from tensile testing and these properties are affected by the geometry, size and properties of the reinforcements. The Modulus of Elasticity and Poisson’s ratio are determined by measuring the strains during the elastic deformation part of the test, typically below the strain levels of 0.5%.

Uniaxial Tension Test (ASTM D638)

Figure 4: Uniaxial Tension Test on a Material Sample as per ASTM D638

. The stress (σ) in a uniaxial tension test is calculated from;

$$\sigma = \text{Load} / \text{Area of the material sample} \quad \ldots\ldots(1)$$

The strain(ε) is calculated from;

$$\varepsilon = \delta l \text{ (change in length)} / l1 \text{ (Initial length)} \quad \ldots\ldots(2)$$

The slope of the initial linear portion of the curve (E) is the Young’s modulus and given by;

$$E = (\sigma 2 - \sigma 1) / (\varepsilon 2 - \varepsilon 1) \quad \ldots\ldots(3)$$

3 Point Bend Flexure Test (ASTM D790)

Three point bending testing is done to understand the bending stress, flexural stress and strain of composite and thermoplastic materials. The specimen is loaded in a horizontal position, and in such a way that the compressive stress occurs in the upper portion and the tensile stress occurs in the lower portion of the cross section. This is done by having round bars or curved surfaces supporting the specimen from underneath. Round bars or supports with suitable radius are provided so as to have a single point or line of contact with the specimen.

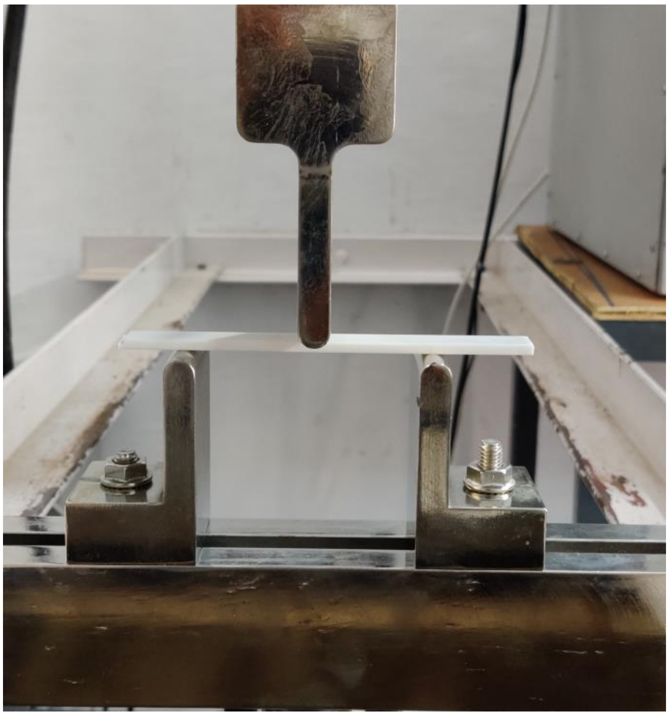


Figure 5: 3 Point Bend Test Setup at AdvanSES as Per ASTM D790

The load is applied by the rounded nose on the top surface of the specimen. If the specimen is symmetrical about its cross section the maximum tensile and compressive stresses will be equal. This test fixture and geometry provides loading conditions so that specimen fails in tension or compression. For most composite materials, the compressive strength is lower than the tensile and the specimen will fail at the compression surface. This compressive failure is associated with the local buckling (micro buckling) of individual fibres.

4 Point Bend Flexure Test (ASTM D6272)

The four-point flexural test provides values for the modulus of elasticity in bending, flexural stress, flexural. This test is very similar to the three-point bending flexural test. The major difference being that with the addition of a fourth nose for load application the portion of the beam between the two loading points is put under maximum stress. In the 3 point bend test only the portion of beam under the loading nose is under stress.

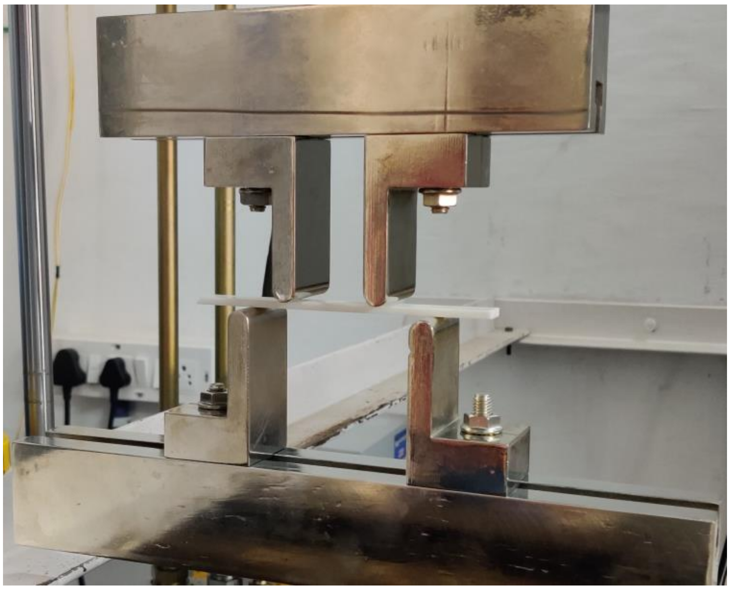


Figure 6: 4 Point Bend Test Setup at AdvanSES as per ASTM D6272

This arrangement helps when testing high stiffness materials like ceramics, where the number and severity of flaws under maximum stress is directly related to the flexural strength and crack initiation in the material. Compared to the three-point bending flexural test, there are no shear forces in the four-point bending flexural test in the area between the two loading pins.

Poisson’s Ratio Test as per ASTM D3039

Poisson’s ratio is one of the most important parameter used for structure design where all dimensional changes resulting from application of force need to be taken into account. For this test method, Poisson’s ratio is obtained from strains resulting from uniaxial stress only. ASTM D3039 is primarily used to evaluate the Poison’s ratio.

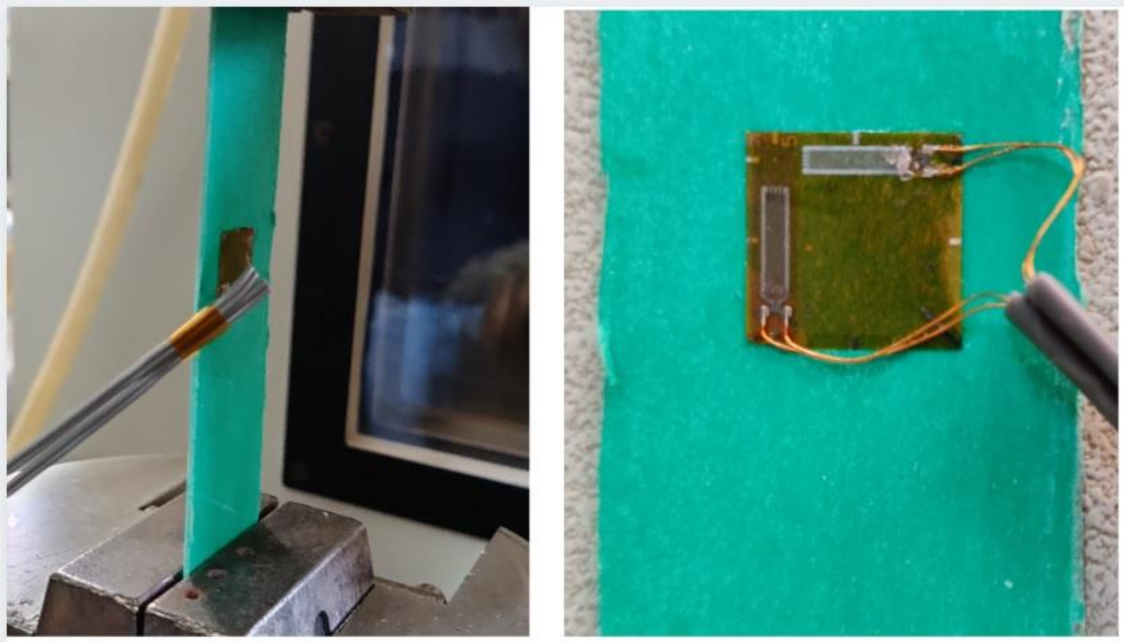


Figure 7: Poisson’s Ratio Test Setup as per ASTM 3039 at AdvanSES

Testing is performed by applying a tensile force to a specimen and measuring various properties of the specimen under stress. Two strain gauges are bonded to the specimen at 0 and 90 degrees to measure the lateral and linear strains. The ratio of the lateral and linear strain provides us with the Poisson's ratio.

Flatwise Compression Test

The compressive properties of materials are important when the product performs under compressive

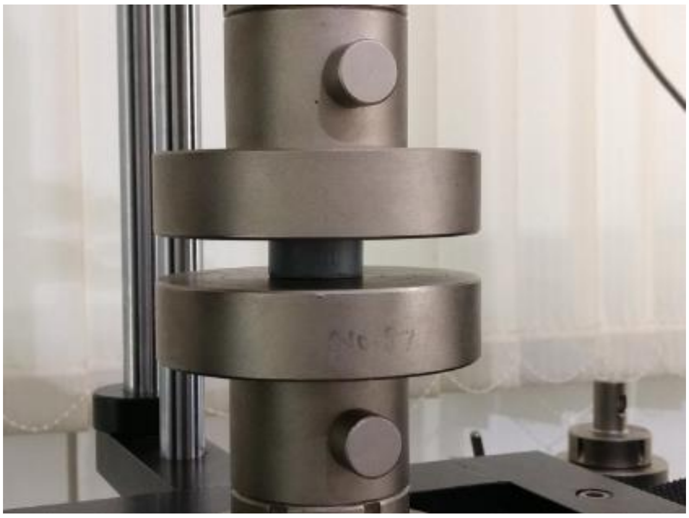


Figure 8: Flatwise Compression Test Setup as per ASTM C365 at AdvanSES

loading conditions. The testing is carried out in the direction normal to the plane of facings as the core would be placed in a structural sandwich construction.

The test procedures pertain to compression call for test conditions where the deformation is applied under quasi-static conditions negating the mass and inertia effects.

Combined Loading Compression Test

ASTM D6641 is the testing specification that determines compressive strength and stiffness of polymer matrix composite materials using a combined loading compression (CLC) test fixture. This test procedure introduces the compressive force into the specimen through combined shear end loading.

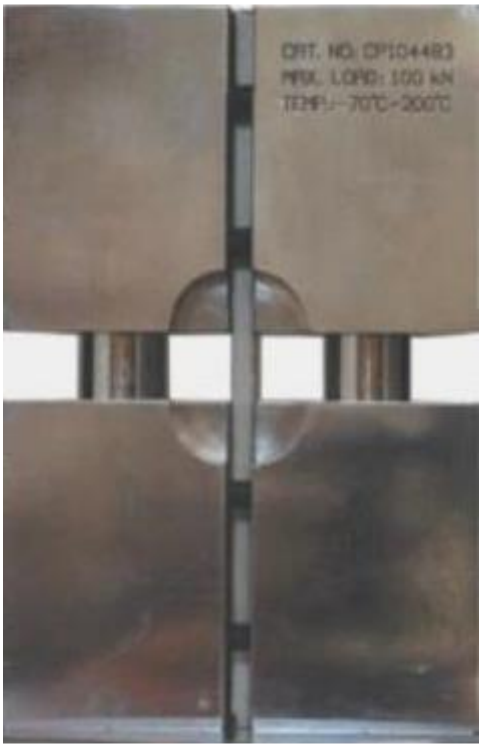


Figure 9: Combined Loading Compression Setup with Unsupported Gauge Length

ASTM D6641 includes two procedures; Procedure A: to be used with untabbed specimens such as fabrics, chopped fiber composites, laminates with a maximum of 50% 0° plies. Procedure B: is to be used with tabbed specimens having higher orthotropic properties such as unidirectional composites. The use of tabs is necessary to increase the load-bearing area at the specimen ends.

Fatigue Test

ASTM D7791 describes the determination of dynamic fatigue properties of plastics in uniaxial loading conditions. Rigid or semi-rigid plastic samples are loaded in tension (Procedure A) and rigid plastic samples are loaded in compression (Procedure B) to determine the effect of processing, surface condition, stress, and such, on the fatigue resistance of plastic and reinforced composite materials subjected to uniaxial stress for a large number of cycles. The results are suitable for study of high load carrying capability of candidate materials. ASTM recommends a test frequency of 5 hz or lower.The tests can be carried out under load or displacement control.

Figure 10: Axial Fatigue Samples under Test at AdvanSES as per ASTM D7791

The test method allows generation of a stress or strain as a function of cycles, with the fatigue limit characterized by failure of the specimen or reaching 10^7 cycles. The 10^7 cycle value is chosen to limit the test time, but depending on the applications this may or may not be the best choice. The maximum and minimum stress or strain levels are defined through an **R** ratio. The **R** ratio is the ratio of minimum to maximum stress or displacement that the material is cycled through during testing. For this standard, samples may be loaded in either tension or compression.

Summary:

A variety of standardized mechanical tests on composite materials including tension, compression, flexural, shear, and fatigue have been discussed. These mechanical properties of polymers, fiber-reinforced polymeric composites immensely depend on the nature of the polymer, fiber, plies, and the fiber-matrix interfacial bonding. Advanced engineering design and analysis applications like Finite Element Analysis use this mechanical test data to characterize the materials. Second part of the paper will show the use of these mechanical characterization tests in FEA software like Ansys, Abaqus, LS-Dyna, MSC-Marc etc.

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