

Philosophy of Selecting ASTM Standards for Mechanical Characterization of Polymers and Polymer Composites

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Abstract: Mechanical characterization of newly developed polymers and composites are the basic measurements that are used to check the potential of the material towards its usage in various applications. Young researchers who are new to the field of materials science often find it difficult in selecting the specific testing standards for their novel materials. This review article provides a detailed explanatory of the various ASTM standards that are used for analyzing the basic mechanical properties of polymer composite materials. The standard dimensions of the test specimens and the mechanical testing parameters that are universally followed in different testing phases are illustrated for the ease of research.

Keywords: ASTM Standards, ISO Standards, DIN Standards, Mechanical Characterization, Polymer composites

Introduction

Development of novel polymer composites is a unique area of study having its recent classifications towards both hybrid-synthetic and bio-composite materials, for versatile applications. Once a material is developed, the primary focus is to check for its mechanical strength that justifies its quality. Mechanical characterization of the material is checked under specified standards universally. The most widely preferred testing standard used by researchers who work with polymers is the American Standard for Testing and Materials (ASTM) [1]. ASTM is one of the subdivisions under the International Organization of Standardization (ISO). Both the ASTM and ISO although represented by different codes, have the common specifications and parameters for testing plastic oriented materials. Polymers and polymer composites are processed through different methods based on the properties of the base matrix material. Processing techniques like injection moulding, compression moulding, extrusion moulding, in-situ method, hand layup method and even stir casting [2] are few of the most common methods. Similarly, reinforcement in the form of laminates, short fibers, long fiber in various orientations and particulates [3] are widely studied by researchers. Irrespective of the fabrication method or the type of reinforcement, the testing methods always remains common while investigating the mechanical properties of a material [4].

ASTM is commonly followed by western countries while the ISO standards are followed in UK and other Asian countries. DIN is another familiar standard that is used extensively for analyzing the properties of mechanical components in European countries. DIN is abbreviated as "Deutsches Institut für Normung" meaning "German Institute of Standardiation" [5]. It is also known as the European ISO. Any international expertise of a specific field can suggest a DIN standard for mechanical characterization, which when found suitable is approved and accepted by the DIN committee. The standards are reviewed every five years and if a standard no longer comprehends to current technology, it is revised or withdrawn. ASTM is the universally recognized standard. It is nowadays accepted globally in scientific articles and for research experimentation. An ASTM code consists of a 'Prefix

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letter' followed by a series of numbers. The prefix letter ranging from A to G, signifies the type of material that is to be tested. This is briefly tabulated in Table 1 [6].

Table 1. ASTM Prefix with material correlation

ASTM Prefix	Material
A	Steel and Iron
B	Nonferrous metals
C	Concrete, Masonry and Ceramic Materials
D	Miscellaneous materials
E	Miscellaneous subjects
F	Materials that are developed for specific applications
G	Corrosion, Deterioration and Degradation of materials

Since Plastics and polymer composites come under miscellaneous materials in Table 1, the ASTM prefix 'D' is used to denote all the testing methods for plastics based materials. This article discusses about the most suitable ASTM standards for testing the mechanical properties of polymer and polymer composites that are reinforced with synthetic or natural fibers. An equivalent comparison of the internationally recognized standards is tabulated in Table 2, providing researchers the most suitable standard for testing.

Table 2. Equivalence of testing standard codes

PROPERTY	ASTM	ISO	DIN
Tensile	ASTM D638	ISO 527	DIN EN ISO 527-2
Flexural / Bending	ASTM D790	ISO 178	DIN EN ISO 178
Impact	ASTM D256	ISO 180	DIN EN ISO 180
Compression	ASTM D695	ISO 604	DIN EN ISO 604
Fatigue	ASTM D3479	ISO 13003	DIN EN ISO 13003
Shear	ASTM D732	ISO 14130	DIN EN ISO 14130
Hardness	ASTM D2240	ISO 868	DIN EN ISO 868
Wear	ASTM D1044	ISO 15082	DIN EN ISO 15082
Water Absorption	ASTM D570	ISO 62	DIN EN ISO 62

The Tensile tests

ASTM D638

The equivalent to ASTM D638 is the ISO 527-2. Usually the ASTM D638 is preferably carried out on a Universal Testing Machine than an extensometer. It is performed to determine the tensile properties of polymers reinforced long fibers like synthetic or natural fibers, fibers in the form mats, carbon fibers, Kevlar etc., The basic data that are derived through this test are the Tensile strength, Tensile modulus, Elongation and the Poisson's ratio [7]. The thickness of the test specimens under this ASTM standard should lie in between 1 to 14 mm [8], based on the application that the material is being developed for, although the most commonly used thickness by most researchers under this ASTM is 3.2 mm. Specimens having thickness lower than 1 mm should be analyzed under ASTM D882 [9]. The mechanical load applied during the testing phase should lie between 5 to 10 kN for testing plain polymers and between 30 to 50 kN for reinforced polymers. ASTM D638 is further classified into two major types, Type I and Type IV. Both these vary in the dimension parameters of the prepared test specimens.

The Type I ASTM D638 is commonly followed for injection moulded specimens having an overall length of 165 mm and a width of 13 mm at the neck and 19 mm at each ends where the specimen is to be held in the gripper [10]. A gauge length of 50 mm is preferred. The Type IV ASTM D638 must have an overall length of 115 mm, a gauge length of 25 mm and a width of 6 mm. For the type IV, the thickness of the specimen should also specifically be machined to 3 mm. Irrespective of the type, the

shape of the test specimen under ASTM D638 must replicate a dog-bone shape (if the specimen is rectangular, having a length width and thickness) or a dumbbell shape (if the specimen is circular, having a diameter) as shown in Figure 1.

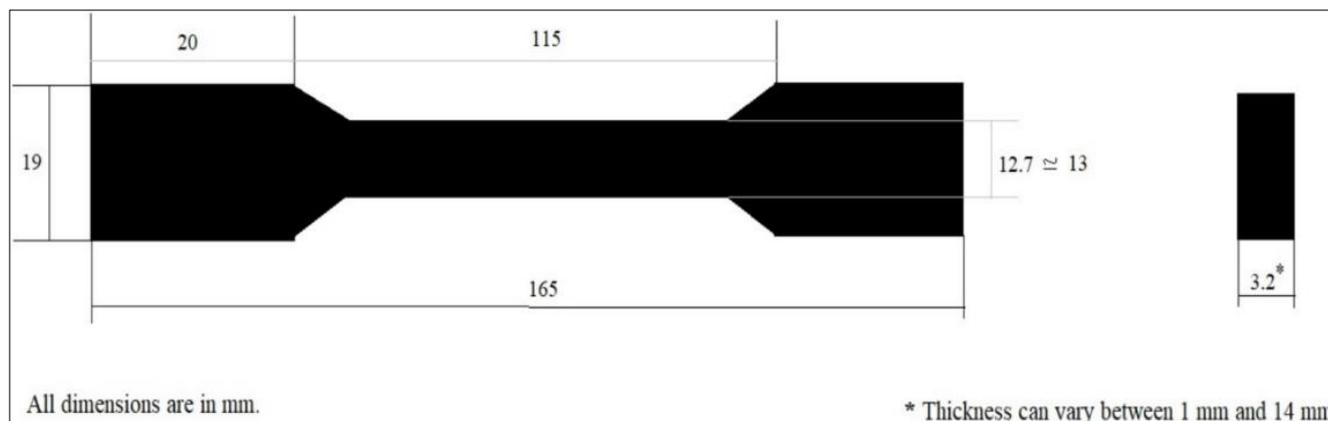


Figure 1. Dimensions of Tensile test specimen under ASTM D638

The cross head speed movement for the ASTM D638 varies between 5 mm/min and 500 mm/min based on the ductility and thickness of the test specimen [11]. If a material is very soft like a polymer reinforced with plasticizers or rubber, it requires faster cross head speed movement and for brittle materials it is vice versa. The most commonly used cross head speeds that is used for testing plain polymers and polymers reinforced with synthetic or natural fibers are 5 mm/min (if the thickness is 3.2 mm) [12,13] and 10 mm/min (if the thickness of the test specimen is above 4 mm) [14]. But experiments carried out on tough materials like polyamide have used a cross head speed of upto 500 mm/min [15].

ASTM D882

This ASTM standard is used explicitly for materials having a thickness of below 1 mm. Plastic materials and composites like thin films, thin sheets and thin laminates should be tested for tensile properties using ASTM D882 to achieve precise results [16]. The uniform thickness of very thin specimens may vary upto 10% and for specimens nearing 1 mm thickness, the uniform thickness can vary around 5%. The specimens should be rectangular in shape with width varying between 5 and 25.4 mm. The standard testing maximum overall length of the specimen must be 250 mm but a minimum overall length of 100 mm is mandatory. A gauge length of 50 mm considering either sides of clamping is widely acceptable in the ASTM D882. In common terms the dimensioning for this ASTM standard may also be expressed in terms of the length of the specimen being 8 times its width.

A specimen tested under ASTM D882 can provide only one tensile property at a time, either tensile strength or tensile modulus due to the very low break force. Literatures state that atleast 5 specimens must be tested to achieve the mean and precise tensile strength, while another 5 separate specimens should be prepared to be tested to measure the tensile modulus in similar fashion [17]. Since the thickness of the specimens under ASTM D882 is very low, discussion of the elongation parameter is generally not considered unless the test specimen is extremely elastic in nature. ASTM D882 does not suggest using extensometers to measure strain. The grippers of a UTM that is used for holding specimens to be tested for tension under ASTM D638 and ASTM 3039 are generally two jaw pneumatic or manual operated grippers while for the ASTM D882 self-tightening roller grippers are preferred to avoid slippage and breaking of the specimen at the ends. For least case scenario due to unavailability of self-tightening roller grippers, rubber jaw grippers with tabbed end specimens can be used in ASTM D882 maintaining a minimum material gripping rubber face of 25 mm x 25 mm. In spite of the being very thin specimens, the cross head movement speed is followed as per the ASTM D638 standard ranging from 5 mm/min to 500 mm/min based on the materials elasticity.

ASTM D3039

The ASTM D3039 must be followed for light weighing materials specifically designed for applications like automotive and aeronautical components. Secondly only the polymer composites that are reinforced with short fibers or in particle form should be considered for testing under this ASTM standard [18]. An author who is using the ASTM D3039 for testing and writes a scientific article regarding the same must discuss the tensile strength and tensile modulus parameters [19], but the elongation details optionally need not be considered for discussion [20]. This is due to the fact that the reinforced short fibers or particulates may not show significant variation in the elongation of the matrix material, which is not the case in the long fiber reinforced composites considered under ASTM D638. But if the author finds large variations in the elongation parameter in cases where novel materials tend to provide so or higher reinforcement ratio provides significant variation in the elongation, then it may be discussed during the explanatory briefly.

The shape of the test specimen under ASTM 3039 must be only rectangular in form. Dog-bone shaped is not preferred here since necking phenomenon during elongation is not studied in-depth, simply because of the fact that this testing method focuses on the application based forum thereby omitting the gauge length which is not necessarily needed [21]. Secondly, machining a test specimen to a dog-bone shape may also be a tedious process for materials processed under methods other than injection moulding. Under the ASTM D3039, the overall dimensions of the specimen is calculated using the formula represented in Equation 1.

$$\text{Overall Length of Specimen} = \text{Gripping length} + 2(\text{Width of specimen}) + \text{Gauge length} \quad (1)$$

In most literature, authors opting to test their specimens under ASTM D3039 consider fabricating their specimens to an overall length of 250 mm. The mechanical load applied during the testing phase should lie between 30 to 50 kN for glass fiber and natural fiber reinforced polymers and between 100 to 250 kN for carbon fiber reinforced polymers. Cross head speed during testing is followed similar to the procedure of ASTM D638 [22].

Flexural Test (ASTM D790)

The ASTM D790 is equivalent to the ISO 178 standard [23]. There are two types of bending testing methods under ASTM D790 based on the fixed points of load application. Three point bending test is carried out on specimens that break below 5% strain [19, 24, 25]. If a specimen does not undergo failure until 5% break then it must be subjected to 4 point bending test. Further detailed description of the four point bending test can be obtained through ASTM D6272 standard [26]. According to the ASTM D790 the span length of the fixtures on which the specimens are placed during the three point bending test must be 10% of the length of the specimen from either ends [27]. The standard overall length of the ASTM D790 specimen is 150 mm, considering which the specimen should be placed on a fixture at 15 mm from either ends [14]. The vertical load should be applied at the exact center of the specimen, which is 75 mm as represented in Figure 2.

Test specimens under ASTM D790 have a width of 13 mm and usually have a thickness of 3.5 mm which is the standard measurement but the thickness can vary mentioned similar to that of the ASTM D638 while focusing on specific applications. The cross head speed of the strain force applied is preferred to be 1 mm/min for the three point bending test and 10 mm/min for the 4 point bending test. But most researchers commonly use a cross head speed of 2 mm/min and 5 mm/min [28] for the three point bending test for reinforced polymer composites.

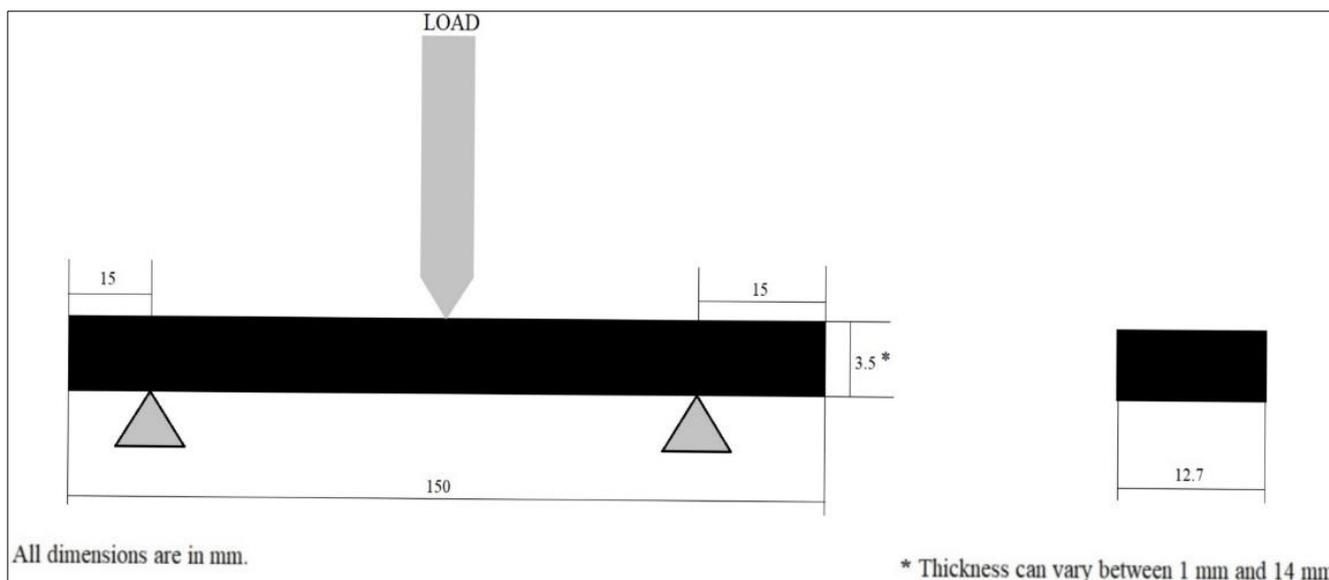


Figure 2. ASTM D790 test specimen depicting three point bending test

3. Impact Test (ASTM D256)

The ASTM D256 is similar to the ISO 180 standard which recommends the Izod impact test as the standard testing procedure over the Charpy test method. While the ASTM method specifies the dimensions of the test specimen to be 64 mm in length, 12.7 mm in width and 3.2 or 6.4 mm in thickness, the ISO standard specifies a specimen length of 80 mm, width of 10 mm and a thickness of 4 mm [29]. A V-notch on the specimen is cut exactly at the mid length of the specimen and the angle of the notch should be 45 degrees. The depth of the notch considered in the ASTM standard is 2.5 mm and for the ISO standard it is 2 mm respectively. The V-notch is cut along the width of the specimen as shown in Figure 3.

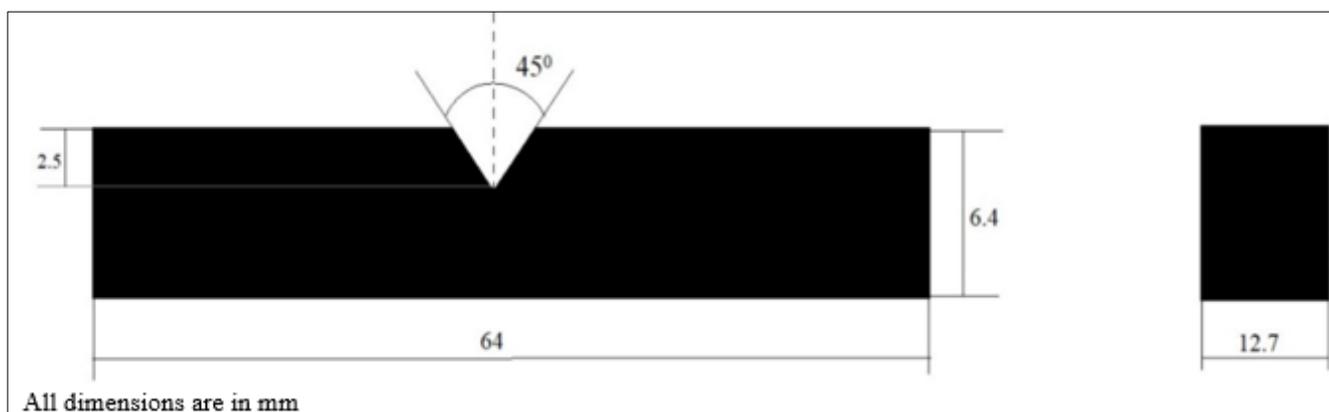


Figure 3. Dimensions of notched impact test specimen under ASTM D256

Albert et al. [30] examined ten distinct polymeric materials under the Izod impact test considering the ASTM standard. On testing the Fused Deposition Moulded (FDM) polymers, immense detail was obtained regarding the impact properties based on the various orientations and the angles of the reinforcements. For specific cases where the developed polymer or composite is specifically focused on application based forum a notch need not be cut, in such cases the area of cross section of the energy absorbed must be considered completely for calculating the impact strength. The un-notched testing of polymers is generally covered under ASTM D4812 [31]. If 'ASTM standard' is followed for testing, the unit of the final result is represented in Joule per meter (J/m) [19]. If 'ISO standard' is followed, then the resultant impact strength is represented in Kilo-Joule per square meter (kJ/m^2). While the Izod impact

test is generally tested using the pendulum swing impact method [32], vertical drop weight method is also performed specifically by researchers for testing thermoplastic pipes. The detail of vertical drop method can further be obtained from the ASTM D2444 standard [33]. Aravind Raj et al. [34] performed a comparative study on ABS and PLA composites that were fabricated through 3D printing. Tensile, flexural and impact properties to specific ASTM standards were analyzed to derive precision results.

Compression Test (ASTM D695)

For the compression test, specimens can be prepared in the shape of either blocks or cylinders. For the block shaped specimens, the dimensions are 12.7 mm in length, 12.7 mm in width and 25.4 mm in height [35]. If cylindrical specimen are to be fabricated for testing, the specimen should have a diameter of 12.7 mm a length of 25.4 mm. ASTM D695 performed on a UTM provides data about the compressive strength, compressive yield point and modulus but if compressive strain is to be measured then an extensometer is required [36]. Other loading and testing parameters are followed similar to that of the ASTM D638 tensile testing standard. The ASTM D695 is generally used for testing rigid plastics [15]. The dimension of the test specimen to be fabricated to ASTM D695 standard for compressive test is shown in Figure 4.

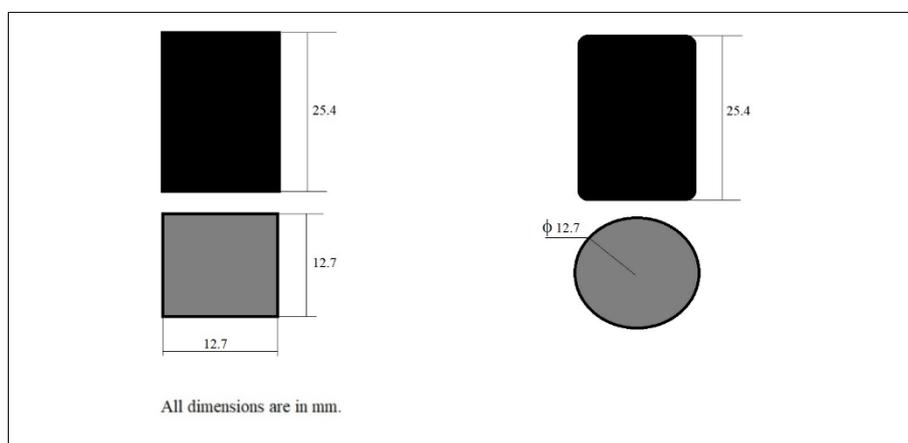


Figure 4. Dimensions of Compression test specimen under ASTM D695

Fatigue Test

ASTM D3479

This method is used to test the fatigue damage of continuous or discontinuous fiber reinforced composites by using discontinuous cyclic loading cycle intervals. The specimen dimensions and loading parameters for this method is replicative to that of the ASTM D3039 standard [37]. There are two different methods through which the ASTM D3479 is performed.

Procedure A-A

In this method the test specimen is subjected to repetitive constant amplitude stress cycles and the test control parameter may be described using engineering stress.

Procedure B-A

In this method the test specimen is subjected to repetitive constant amplitude strain cycles and the test control parameter may be described using engineering strain.

ASTM D7791

The ASTM D7791 is used for measuring the fatigue properties of plastic materials under uniaxial stress for a large number of cycles [38]. The test frequency varies from 1 to 25 Hz but the preferred loading is 5 Hz [39]. There are two different methods through which the ASTM D7791 is performed.

Procedure A

In this method the fatigue test is performed under tension loading.

Procedure B

In this method the fatigue test is performed under compressive loading. This is recommended only for rigid plastics.

Shear Test (ASTM D732)

Shear strength is obtained by dividing the load by the area of the sheared edge and the ASTM D732 suggests the diameter of the test specimen to range from 0.127 mm to 12.7 mm [40]. Researchers use this method primarily to examine the shear strength of organic plastics [41], while strain measurement to obtain shear stiffness is not possible through this method [15].

Hardness Test (ASTM D2240)

The ASTM D2240 is specially suggested for the Shore A and Shore D hardness measurements. This ASTM is performed on soft materials like plastics and rubber, where Shore A is used for softer materials and Shore D is used for harder plastics. The dimension of the test specimen under ASTM D2240 is generally 6.4 mm thick. The indenter is pressed parallel against the test specimen and the Durometer hardness is read within a very short depression time of as less as 1 s [42]. Test loads are 10 N for Shore A test and 50 N for Shore D method [43]. Simon et al. [44] used the durometer to determine the hardness characteristics of various soft and hard plastics and provide detailed explanatory of the equipment's components and working procedure. In the absence of a durometer and unable to perform the Shore D hardness test, Rockwell [19] and Brinell [45] hardness test procedures are widely adopted by researchers as alternative methods to determine the hardness of a polymeric material.

Abrasion Test (ASTM D1044)

In the case of plastics, Taber abrasion test is the most preferable method to determine the ability of the material to withstand mechanical friction. Taber means, a rotating drum. The abrasion is calculated by considering the weight loss of the material (in mg.) to the number of rotational cycles of the abrasion wheel/disc/drum. The dimensions of the test specimen under the ASTM D1044 should have a diameter of 4 inches (if circular) or 4 sq. inch plate (if square in shape). The weight loading parameter is considered at 250, 500 or 1000 gms, based on the hardness of the material [46]. ASTM D1044 is used to study the abrasion of plain polymers and plastics that are reinforced with any kind of material like natural fibers, minerals, metal, ceramics, etc. Such materials are specifically developed for applications where sliding, rubbing and scraping are predominant like automobile windows, plastic gears, gears and similar products [47, 48].

Water Absorption Test (ASTM D570)

The Water Absorption Test is performed for all polymeric samples that are reinforced with materials that have the inherent tendency to absorb moisture, like natural fibers, nano-clay, minerals, etc., [47, 49] In some cases biopolymers that are derivatives from natural plant extracts, like Poly Lactic Acid [50] are also subjected to water absorption test since they may tend to absorb moisture and undergo swelling when exposed to such environments for long periods of time. The ASTM D570 is the most widely used standard for water absorption test. It suggests initial drying of the test specimen in a furnace for specified time and temperature based on the specimens thermal properties [51]. Post drying, the specimens are cooled at room temperature and then immersed in normal water for a period of 24 h [52, 53]. The experiment is carried out at room temperature which is best suggested to be around 23°C. The time period, 24 h of immersion of the specimen in water is considered to be sufficient enough, since maximum amount of water uptake by any material that has the tendency to absorb moisture takes place in the first 24 h of immersion beyond which there is no significant increase in absorption [54]. The specimen upon



removal from water, must be wiped dry on the surface and measured to determine the increase in weight due to moisture absorption. The formula used to calculate the Rate of Water Absorption by the specimen is depicted in Equation 2 [4, 14].

$$\%WA = [(W_w - W_d) / W_d] \times 100 \quad (2)$$

where, %WA represents Percentage of Water Absorbed, W_w is the wet weight of the specimen and W_d is the dry weight of the specimen. The specimens that are tested under ASTM D570 must have a two inch diameter if circular, or 2 inch per side if square in shape. The thickness of the specimen must be either 0.125 inches or 0.250 inches [55]. Generally a fractured specimen that has earlier been subjected to any one of the mechanical tests is considered for the water absorption test since the fractured surface would provide better exposure of the reinforced material to the moisture. If the specimen is not fractured, it would possess a smooth surface which may prevent the reinforced materials from being completely exposed to water during testing thereby resulting in errors.

Conclusions

Based on the above discussions, selection of the most appropriate ASTM standards for polymeric materials and polymer based composites can be conclusively nominated. Analyzing the basic mechanical characterization, their test loading parameters and dimensions to which the test specimens have to be fabricated can be critically designated for research purpose to obtain standardized results.

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