WHITEPAPER

Your Extensive Guide to the Properties of 3D Printing FFF Filaments

BCN3D

Abstract

Once you have fully understood the physical and mechanical properties of the filaments at your disposal, choosing the correct material for your 3D printing project is easy! This whitepaper starts off with a list of the physical and mechanical properties of plastic materials from a Technical Data Sheet. Through a tensile test, we then gathered significant information about BCN3D's filaments in terms of the essential physico-mechanical properties: analysis of the stress vs strain curve, ultimate tensile strength, elongation at break, and Young's modulus. From these results, the filaments were categorized into composite, rigid, semi-flexible or elastomeric. We continued evaluating properties by looking at impact resistance, which can be improved by material toughening. To evaluate heat resistance, we performed a Heat Deflection Temperature test to see at which temperature the material will bend and lose shape retention. We also tested the chemical resistance of the materials against acids, bases, water, or organic solvents.

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Introduction

With every print job, comes its own application and specific requirements. There's a lot of information to sift through when it comes to making the right decision for the filament you use. That's why we've created this whitepaper to give a breakdown of each property and an in-depth discussion of how each filament performs based on that criteria. Keep reading for a list of all physical and mechanical properties of plastic materials, an explanation of the essential physico-mechanical properties a tensile test can provide, and a deep dive into impact, heat, and chemical resistances.

List of Physical and Mechanical Properties of Plastic Materials

A Technical Data Sheet (TDS) includes all the technical information on materials so that you can make an informed decision. Below is a simplified list of the most common physical and mechanical properties found in the Technical Data Sheets (TDS) of plastic materials. For a complete definition of each property, please refer to TEXTBOOK[1].

Relevant mechanical properties:

- *Ultimate tensile strength:* the maximum stress that a material can withstand before breaking when pulled or stretched longitudinally.
- *Elongation at break*: the maximum elongation (or strain) that a material can reach, when pulled at its breaking point.
- *Young´s modulus*: also known as modulus of elasticity, it is a measure of the material's stiffness.
- *Flexural strength*: the maximum stress that a material can withstand before breaking when twisted during a flexural test.
- *Flexural modulus*: analogue to Young's modulus of elasticity, but measured during the flexural test. Indicates the stiffness of the material.
- *Ultimate compressive strength*: the maximum compressive stress that the material can withstand before collapsing.
- *Creep resistance*: the resistance to irreversible deformation caused by prolonged static loads.
- *Impact strength*: the resistance to a sudden impact with a high-velocity hammer.
- *Hardness*: the resistance to a localized deformation caused by a penetrating or abrasive object.
- *Coefficient of friction:* measurement of the resistance to movement when the material is rubbed against a reference surface, typically steel.
- *Abrasion resistance*: the resistance to the scratching action of a rough surface on the material.

[1] Brown, Roger, ed. Handbook of polymer testing: physical methods. CRC press, 1999.

Thermal properties:

- *Heat deflection temperature*: the temperature at which the material starts to deform when a load is applied.
- *Coefficient of linear thermal expansion*: an index of how much a change of temperature affects the dimension of the object.
- *Thermal conductivity*: quantifies the ability to transfer heat through conduction.
- *Specific heat*: the heat necessary to increase a specific mass of material by 1°C.

Other physical properties:

- *Density*: the mass per unit volume.
- *Light transmittance*: indicates the portion of light capable of penetrating a specific thickness of material.
- *Refractive index*: how fast the light travels through the material (very important in optics).
- *Chemical resistance*: how well the material withstands exposure to aggressive chemicals such as acids, bases, and solvents.
- *Water absorption*: relative amount of water that the material is able to absorb if exposed to a humid environment.
- *Weatherability/UV-resistance*: how well the material survives the degrading action of a combination of factors, such as water, heat, and sunlight.
- *Volume/surface resistivity*: indicates how well the material conducts electricity.
- *Gas permeability*: how well different gases can penetrate the material matrix and cross it.

Essential Physico-Mechanical Properties Explained

Tensile testing: tensile strength, elongation at break, and Young's modulus

The **tensile test** is perhaps the most commonly used mechanical experiment, due to its relative simplicity and ability to provide an abundance of information from a single execution. The experiment is usually carried out by pulling a dog bone-shaped bar of material, secured between two vises (*Figure 1*). As the two vises are set into motion, they begin to pull apart the dogbone, causing a deformation along the longitudinal axis. The extent of the deformation is indicated as strain, defined as the ratio between the length of the sample under stress and its original length, which is often expressed as a percentage (*Eq. 1*). Although not strictly equivalent, the terms elongation and strain are often interchanged.

$$Strain = \frac{deformation}{initial\ length} \qquad \varepsilon = \frac{L - L_0}{L_0}$$

The effect of strain on the sample is measured as **stress**, which is the force acting on the section of material transversal to the deformation. The amount of stress generated during the experiment is dependent on the strain applied; how strongly the material resists deformation depends on its stiffness, which is quantified with Young's modulus or elastic modulus, and can be calculated as the slope of the stress vs. strain curve (*Figure 3*).

$$Tensile\ stress = \frac{pulling\ force}{cross\ section} \qquad \sigma = \frac{F}{A}$$

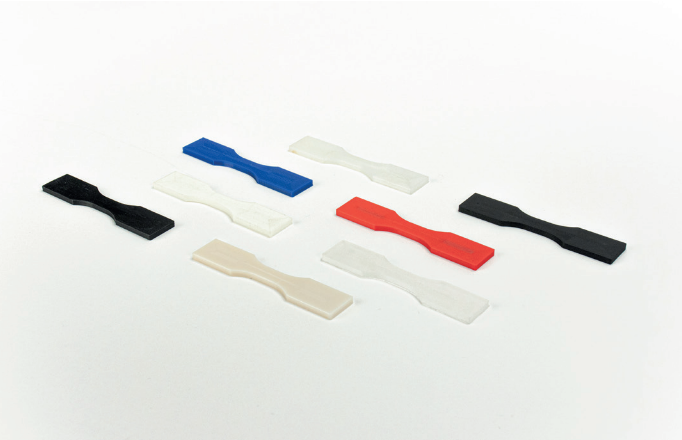


Figure 1: Tensile specimens (dogbones) and tensile test fixtures (Photo courtesy of Shimadzu).

In order to extract the material's critical properties from the test results and understand its behaviour, a stress vs. strain curve is plotted (*Figure 2*). The graph can be divided into two portions, separated by what is called the **yield point**: the point on the curve that indicates when the material stops being elastic and starts a plastic deformation. Within the elastic zone, the material can be stretched while still being able to revert to its original shape. However, deformation in the plastic zone will result in a permanent alteration of the original shape of the sample.

When designing an object, *elongation at yield* and *tensile strength at yield* are both values to consider; structural forces should never go past the yield point, to ensure a maximum service life of the printed part.

Elongation and tensile strength at break correspond to the most extreme conditions the material can withstand before its molecular structure collapses, breaking the part.

Young's modulus can be obtained from the slope of the curve, calculated in the elastic region of the graph.

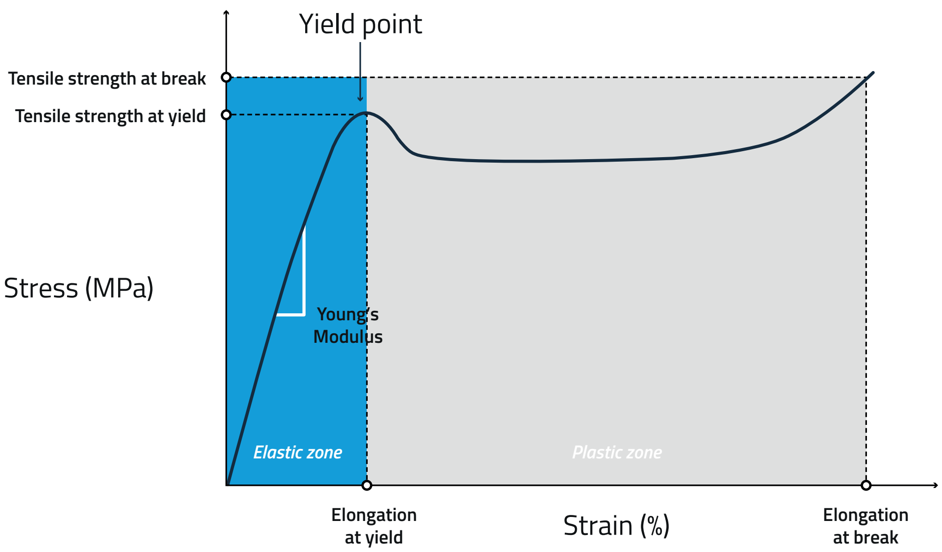


Figure 2: A typical stress vs. strain graph. BCN3D

Depending on the nature of the material, the stress vs. strain curve will differ. This is why the tensile test is so diagnostic; it immediately gives you a complete picture of the mechanical behaviour of the material.

A **rigid and brittle** material, such as PLA, will strongly resist deformation, developing great stress for a low strain (green curve, *Figure 3*).

A **technical** material, such as ABS, has an improved tensile profile, showing a high modulus in the elastic zone and a sharp yield point, followed by a much longer plastic zone (blue curve, *Figure 3*). This translates into a higher **toughness**, meaning that the material is less prone to abrupt fracture, since it is capable of absorbing mechanical energy through a progressive deformation. This is the typical profile of an impact-resistant material, a topic that will be discussed in more detail later in this paper.

A **semi-flexible** material, such as PA, shows an initial degree of rigidity at low strains and is capable of enduring a considerable deformation before failing (orange curve, *Figure 3*).

Elastomeric materials, such as TPU 98A, are characterized by a low Young's modulus, making them soft and pliable, but also resistant to great deformations and impacts (gray curve, *Figure 3*).

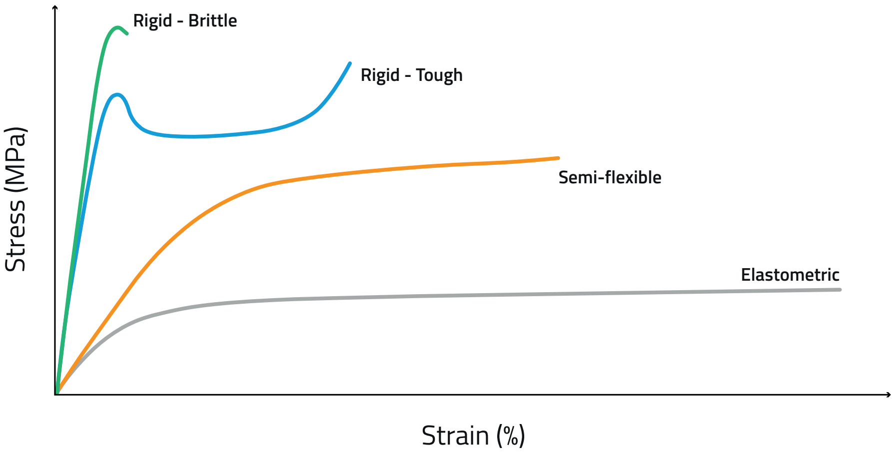
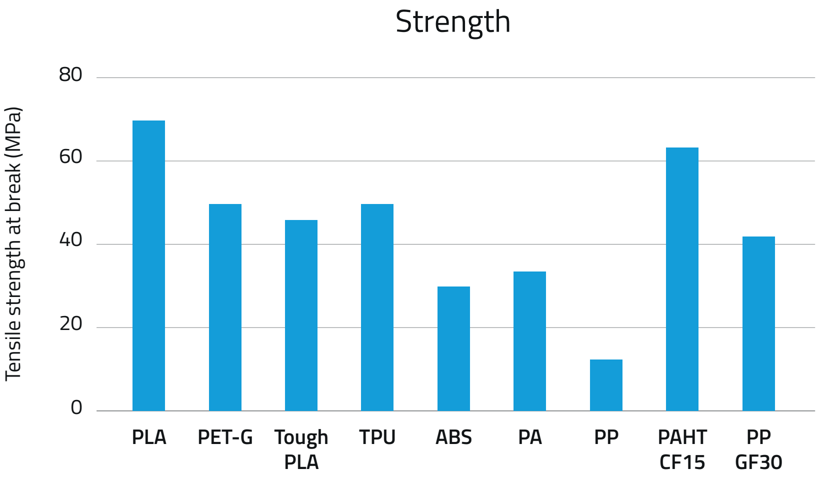


Figure 3: General tensile behaviour of different materials.

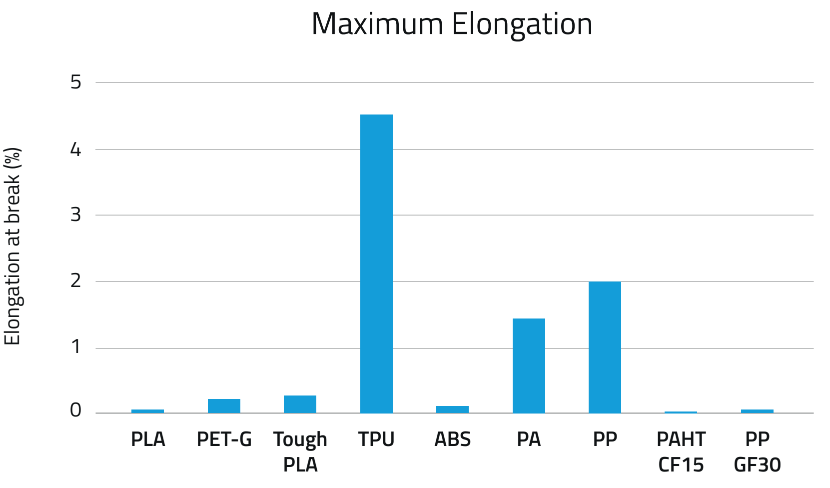
If we were to analyze in detail the tensile properties of all BCN3D filaments, we would observe the above pattern (*Figure 3*). FFF technology allows the processing of a wide variety of filaments, including composite materials, that range from strong and stiff to soft and flexible, for the most demanding applications.

The following graph shows a comparison of the **tensile strength at break** for all BCN3D filaments. It should be noted that, with the exception of PP, all materials show a tensile strength higher than 25 MPa, which makes them suitable for structural parts (*Graph 1*). The strongest materials in our portfolio are PLA and PAHT CF15, which benefit from the innate strength of carbon fibers. Unless you increase **infill density** and/or **part thickness**, PP's softer nature causes it to yield easily, so it cannot be subject to heavy loads.



Graph 1: Ultimate tensile strength of BCN3D Filaments compared.

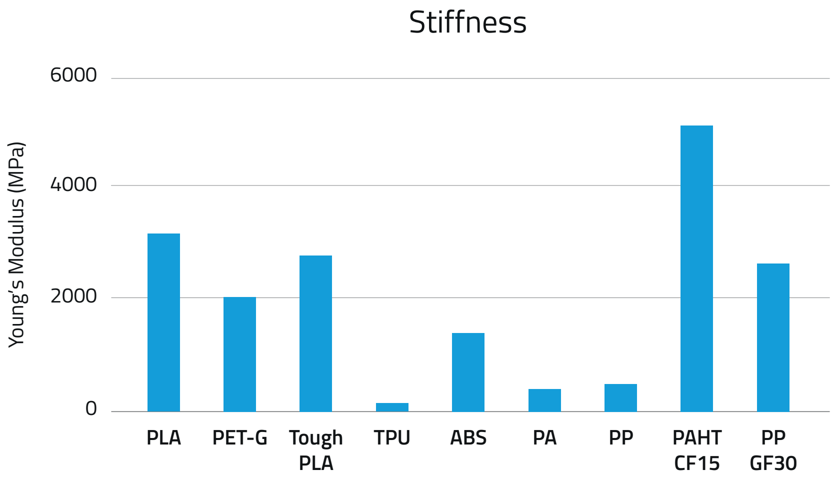
The following elongation at break graph highlights the outstanding **elastomeric** behaviour of TPU 98A (*Graph 2*). In fact, a 3D printed sample of TPU 98A can be elongated to up to 4.5 times its original length before breaking! PA and PP behave as **semi-flexible** materials, with elongations of 143% and 200% respectively. PET-G is notable for its good elongation of 23%, which gives it an overall better mechanical profile in comparison with PLA. Composite filaments PAHT CF15 and PP GF30 are characterized by a low elongation at break, due to the stiffness contributed by the added fibers.



Graph 2: Elongation at break of BCN3D Filaments compared.

Graph 3 shows a comparison of Young's modulus values. In other words, the indicator of the **stiffness** of our filaments.

Here, the composite filaments perform the best: PAHT CF15, with a modulus of 5.1 GPa, and PP GF30, with a modulus of 2.6 GPa. Carbon and glass fiber ensure a high dimensional stability, preventing the polymeric chains from sliding over each other and thus reducing the plasticity of the blend. Among the non-filled materials, our two grades of PLA (PLA and TPLA) display the highest stiffness. PET-G and ABS also offer a decent degree of stiffness, and are therefore best suited for structural applications where deflection is undesired. Flexible and semi-flexible materials, such as TPU 98A, PA, and PP, are characterized by a very low Young's modulus (*Graph 3*).



Graph 3: Young's modulus of BCN3D Filaments compared.

We used the valuable tensile experiment to gather significant information about BCN3D's filaments: analysis of the stress vs strain curve, ultimate tensile strength, elongation at break, and Young's modulus. Based on this evaluation, we were able to create a clear picture of the main strengths and applications of the materials in our portfolio. Subsequently, we divided them into four distinct groups:

- **Composites** (PAHT CF15 and PP GF30): characterized by a great modulus and strength. They are very stiff and therefore have low maximum elongation.
- **Rigid** (PLA, PET-G, Tough PLA, and ABS): with a high ultimate strength and modulus.
- **Semi-flexible** (PA and PP): they are fairly strong, with a low modulus and good elongation.
- **Elastomeric** (TPU 98A): good ultimate strength, very low modulus, and exceptional elongation at break.

Impact resistance

Another important property for consideration when preparing for a 3D print job is **impact resistance**. An impact, such as the hit of a hammer, can be defined as an intense force applied over a small area (i.e. localized) and for a very short time. This generates a great deal of stress on the microscopic structure of an object, so only the toughest materials can absorb direct blows without suffering irreversible damage.

Materials with a high impact resistance are labeled as **tough**. In general, **metals** are very tough materials. Due to their great strength and ductility, they can survive recurrent blows without losing their shape and function (think of the long service life of a bronze bell).

Glassy materials are brittle and normally characterized by a low impact resistance, because of their rigid microscopic structure that rapidly causes the formation of internal stress and rupture.

The behaviour of **plastics** varies according to their chemical composition and degree of crystallinity. As we observed in the previous tensile experiment, plastics can be hard and stiff (e.g. PLA), soft and flexible, (e.g. PP and TPU 98A), or have an intermediate, semi-flexible behaviour (e.g. PA). The impact resistance of plastics follows a similar trend, where hard materials tend to be brittle and, conversely, soft materials are normally much more impact resistant.

If there was no way around this, how is it that polymeric materials have made their way into so many applications in industries and our everyday lives? The answer lies in what is normally referred to as **material toughening**, a discipline that has kept generations of material engineers busy. ABS, for example, was developed in an attempt to increase the toughness of brittle styrenic polymers, through the addition of unsaturated rubbery monomers to the main chain of the polymer. Without acting on the polymer composition, another way to increase the toughness of a material is the **formation of blends**. This can be done with plasticisers or toughening additives, such as solid rubbers or inorganic fillers.

Impact resistance is measured by a special machine that measures the energy absorbed during the impact when a rectangular specimen of material is hit with a hammer; hence the term "impact energy". **Charpy** and **Izod** impact tests are both based on this principle, the only difference being the positioning and direction of the specimen and notch (*Figure 4*). The V-shaped notch's function is to direct the energy of the impact towards a specific direction. This also simulates the corners and imperfections normally present in functional objects.

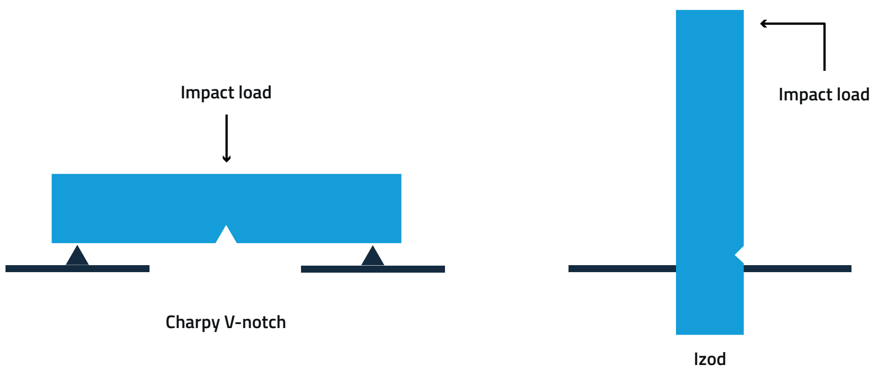


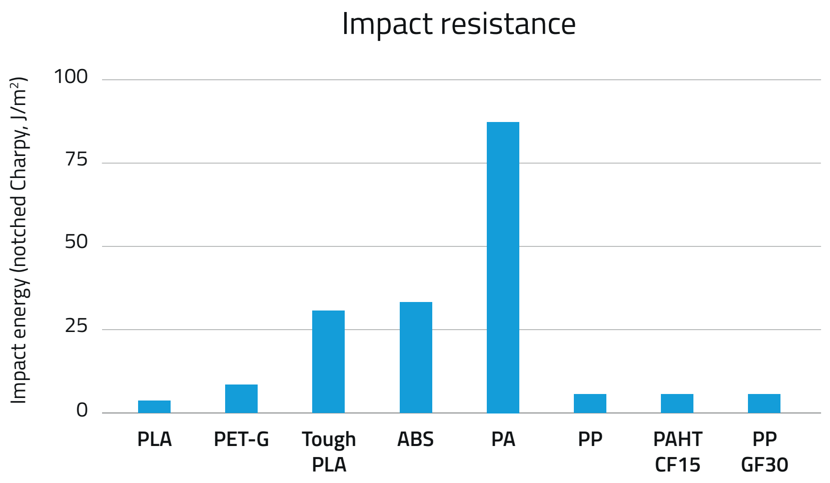
Figure 4: COPYRIGHT: to be redrawn

Graph 4 shows the notched Charpy values of BCN3D Filaments, expressed in KJ/m2. These statistics are a good indication of the impact energy of the different filaments. What immediately stands out is the great impact energy of PA, which is due to its flexibility and **semi-crystalline** nature. Indeed, **polyamides** are characterized by an alternating structure of flexible and crystalline blocks that impart an excellent resistance to impacts and wear.
However, PA is not rigid, and for applications where a combination of stiffness and toughness is required, ABS is the ideal candidate, with a notched Charpy of 32 KJ/m2.

On the other hand, while PP is much more flexible than ABS and PA, it has a very low impact resistance in comparison, due to the weak intramolecular bonds which are characteristic of **polyolefins**. Composite filaments PAHT CF15 and PP GF30 suffer from the high rigidity imparted by the fibers infused in their polymer matrix, and so are not recommended for the manufacture of parts subject to sudden blows.

Regarding the basic filaments, PET-G's impact resistance is better than that of PLA, making it a most suitable alternative for end-use parts. Tough PLA however, shows a similar impact resistance to that of ABS, and makes it the material of choice in the basic segment for moving parts.

TPU 98A was not included in this evaluation, since impact energy was conceived for semi-rigid materials and cannot be measured if the specimen does not break during the test. However, the elastomeric nature of TPU 98A makes it an ideal candidate for flexible bumpers and hammer-proof objects.

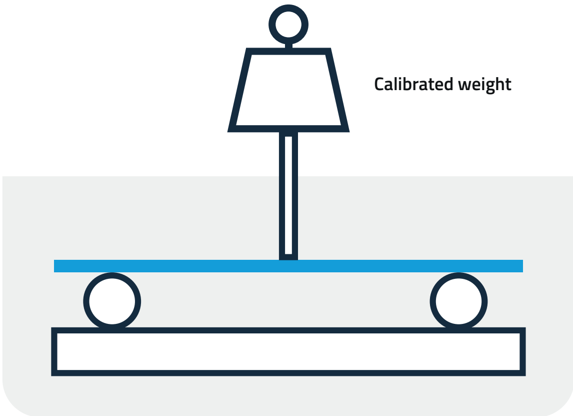


Graph 4: Impact resistance of BCN3D Filaments compared

Heat resistance

Thermoplastics are a class of **polymeric materials** that are characterized by the ability to easily melt with heat and be moulded into a shape in the liquid state. After cooling, a thermoplastic object maintains its given shape indefinitely, and can later be reprocessed by heat in what is called **plastics recycling**. This fast response to heating is advantageous during processing, but can be limiting when final use conditions are demanding. For this reason, it is logical to identify a temperature limit for each material, to ensure safety and prevent distortions and damage caused by heat.

Heat Deflection Temperature (HDT) is considered the industrial standard for testing the heat resistance of a material. The test is performed by submerging a specimen bar of material in a warm silicone bath and progressively increasing the temperature. At the same time, a flexural stress is applied with a calibrated weight, thus provoking the deformation of the specimen once a critical temperature is reached. Heat-resistant materials will bend at a higher temperature than materials that do not withstand heat well. This distinction is very helpful when choosing the correct material for an application where parts can be exposed to a hot environment. As a rule of thumb, you should never place a printed part in an environment above its heat deflection temperature; most likely, your part will eventually lose its original shape, especially if loads or vibrations are applied.

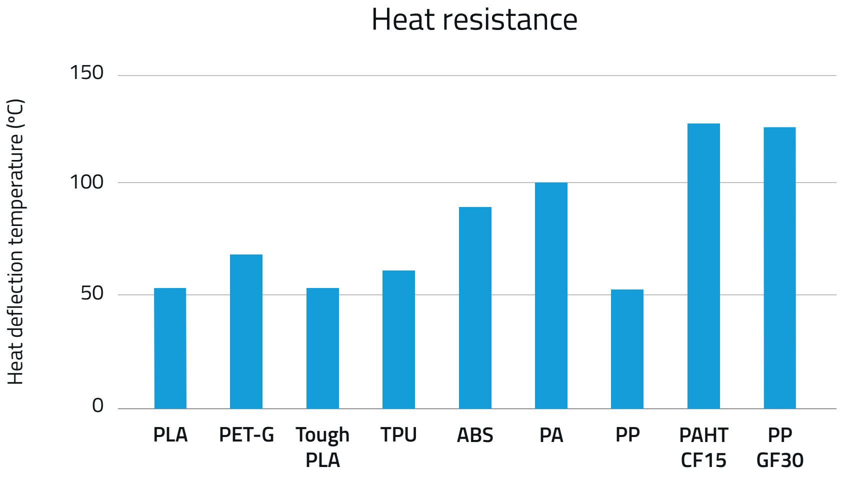


This loss of structural integrity generally happens close to the material Tg, which is the glass transition temperature. This is the temperature at which the polymeric matrix starts losing its rigidity, with the polymer chains uncoiling and gaining mobility. Above its Tg, a polymeric material behaves as a viscous liquid, and tends to occupy the shape of its container.

Graph 5 portrays the HDT values of our materials. Situated between 50 °C and 70 °C, our basic filaments PLA, PET-G, TPLA, and TPU 98A produce parts with an excellent surface finish and mechanical properties, but cannot be exposed to hot environments.

ABS and PA are suitable for intermediate conditions (60-80°C), and optimal in contact with electronics or under solar light (to be used with a UV-absorbing coating).

PP GF30 and PAHT can be exposed to the most extreme environments with temperatures above 100 °C, making them ideal for engine bays.



Graph 5: Heat deflection temperature (0.45 MPa) of BCN3D's filaments.

Chemical resistance

Chemical resistance is another important factor that comes into play for material selection, as it has a direct effect on the service life of any 3D printed object. When the word chemicals is brought up, many people conjure up images of highly corrosive liquids like mineral acids. However, something as harmless as **water** can act as a promoter of **polymer degradation** for many 3D printing materials.

This is the case of PLA, ABS, and PA, whose mechanical properties are drastically reduced in a hot and wet environment. Water not only penetrates the polymer matrix to make it softer, it also accelerates **natural hydrolytic mechanisms** that reduce the length of the polymer chain and thus inhibit the material's ability to support weight and retain its shape.

PET-G is a basic filament that is especially suited to maintaining its properties while exposed to water. Indeed, one of the most common applications of PET polymer is the manufacture of water bottles.

Acids and bases are far more corrosive than water, deteriorating thermoplastics in a matter of hours from first exposure. Resistance to acids or bases is mainly dependent on the chemical composition of the polymer and the presence of acid-sensitive or base-sensitive chemical bonds. ABS, for example, tolerates bases well, while it is not recommended for acids.

6.1 Acids

General chemistry defines **acids** as a family of substances able to release **H+ ions**, which are very reactive and can therefore damage skin and eyes, and modify or deteriorate the chemical bonds that constitute the long organic chains of polymeric materials. While normally more resistant to acids than metals, polymeric materials, such as the thermoplastic filaments used in FFF 3D printing, show different behaviours when exposed to an acidic environment. 3D printed objects could come into contact with commonly used acidic solutions, such as vinegar, bathroom cleaner, battery acid, and fruit juice.
Acid-resistant: PP, PP GF30.
Tolerant to acids (short exposure): PET-G.

6.2 Bases

Bases are a class of **chemical compounds** that strongly react with acids. They can be **inorganic**, such as baking soda and lime, or **organic**, as is the case of amines. Other commonly used base products are soap, kitchen cleaner, bleach, and ammonia. Among plastic materials, the most susceptible to bases belong to the family of organic esters, such as PET-G and PLA. For this reason, they are not recommended for applications where they could come in contact with base substances.
Base-resistant: PP, PP GF30.
Tolerant to bases (short exposure): PA, PAHT CF15, ABS.

6.3 Water

Normally, we consider our survival necessity **water** as a harmless substance. However, it actually makes for an excellent **solvent** and can penetrate between the polymeric chains to weaken the overall structure of a thermoplastic object. This is especially true in the case of highly hygroscopic filaments (which absorb water), whose mechanical properties can vary depending on the relative humidity in the air. Other hydrophobic materials, such as ABS, are susceptible to water-promoted hydrolysis and are not suited to long-term exposure to water.
Water-resistant: PP, PP GF30, PET-G.
Tolerant to water (short exposure): TPU 98A, PAHT CF15.

6.4 Organic Solvents

Organic solvents are **hydrophobic**, **volatile liquids** characterized by **low polarity** and their ability to dissolve organic substances, such as oils, grease, and resins. They are commonly used as cleaning agents, fuel, paint thinner, and reaction medium. When exposed to organic solvents or their vapours, some 3D printing materials start to swell, absorbing the solvent and changing their shape and mechanical properties. The most common organic mixtures that can act as a solvent are alcohols, gasoline, paint remover, acetone, engine oil, brake fluid, and perfumes.
Solvent-resistant: PP, PP GF30.
Tolerant to solvents (short exposure): PA, PAHT CF15, PET-G (reversible swelling).
Complete delamination/dissolution: ABS, PLA.

BCN3D FILAMENTS	Chemical agents			
Materials	Acids	Bases	Water	Solvents
PLA	●○○○○	●○○○○	●●○○○	○○○○○
ABS	●○○○○	●●●●○	●●○○○	○○○○○
PET-G	●●●○○	●○○○○	●●●●○	●●○○○
PA	●○○○○	●●●●○	●●○○○	●●○○○
TPU	●○○○○	●●●○○	●●●○○	●●○○○
PP	●●●●●	●●●●●	●●●●●	●●●●●

A Comparison Chart of BCN3D Filaments

Material	Applications	Mechanical Behaviour	Thermal Behaviour	Chemical Behaviour
PLA	• Architectural mockups • Aesthetic, concept models • Investment casting molds • Low mechanically demanding prototypes	Stiff and strong. Thin walls and corners are fragile.	Very sensitive to heat. Do not use above 40 °C.	Tolerates short contacts with water. Do not clean with aggressive chemicals or solvents.
PVA	• Exceptional adhesion with PLA • Also great in combination with PET-G, TPU and Nylon • Water-soluble supports for partially enclosed cavities and complex geometries • Sacrificial moulds	Weak.	Sensitive to heat. Do not use above 40 °C.	Highly soluble in water. Resistant to organic solvents.
PETG	• Parts in contact with salts, acids and alkalis • Functional prototypes and mechanical parts • Waterproof applications • Structural parts subject to mild stress • Snap-fit joints • Commonly used in beverage bottles	Very strong and rigid. Less fragile than PLA. High durability	Sensitive to heat. Do not use above 60 °C.	Tolerates long-term exposure to water and weak acids. Resistant to alcohols but not strong solvents, such as acetone or toluene.
TPU 98A	• Industrial seals, gaskets, sleeves or hinges • Soft-touch multi-material models or handles • Flexible-joined multi-material models • Protective cases Shoe soles, non-slip surfaces • Springs, seals and shock absorbers • Wheels and rollers	Very strong and flexible. A true elastomer: can be extended up to 4.5 its original length.	Sensitive to heat. Do not use above 50 °C.	Tolerates long-term exposure to water and weak bases. Resistant to alcohols but not strong solvents, such as acetone or toluene.
Tough PLA	• Manufacturing aids • Manufacturing tools • Functional prototyping • End-use parts • Alternative to ABS for large prints	Very stiff and impact resistant. Ideal for jigs and fixtures and end-use rigid parts.	Very sensitive to heat. Do not use above 40 °C.	Tolerates short contacts with water. Do not clean with aggressive chemicals or solvents.

Material	Applications	Mechanical Behaviour	Thermal Behaviour	Chemical Behaviour
PA	• Strong and flexible parts • Structural components exposed to a harsh environment • Parts demanding high fatigue endurance • Bearings, nuts, rivets, washers and gears • Cams, rollers, snap-fit joints and sliding components • Plugs, connectors, jigs and fixtures • Electronic covers and tool handles	Semi-flexible, resistant to impacts and abrasion. Produces indestructible parts.	Heat resistant. Can be used at up to 100 °C.	Better kept dry. Do not clean with aggressive chemicals or solvents.
PP	• Ideal for light parts • Commonly used in bottles, packaging and containers • In automotive for non-structural areas of the body • Plugs and stoppers • Chemically aggressive environments • Living hinges • Pipes, joints and elements in contact with water	Semi-flexible. Much weaker than PA.	Softens with heat. However, it can be treated at 100 °C for short periods.	Chemically inert. It does not interact with water, corrosive solutions, or organic solvents. It can only be attacked by oxidizing agents and UV light.
ABS	• Parts under high mechanical stress • Strong prototypes and end-use parts • Aesthetic models • Commonly used on electronic or appliances cases, suitcases and phones • Precision fits, knobs, lids and buttons • Rigid models with snap-fit joints	Great impact resistance. Ideal for moving parts.	Heat resistant up to 90 °C.	Tolerates short contact with water and base cleaning products. Do not clean with acids or solvents.
PAHT CF15	• Structural and functional parts subject to high temperatures and aggressive environments. • Metal replacement in the automotive industry.	Very strong and stiff composite. Ideal for structural applications and metal replacement in dry environments.	Highest heat resistance, up to 130 °C.	Tolerates short contact with water and base cleaning products. Do not clean with aggressive chemicals or solvents.
PP CF30	• Parts exposed to aggressive and humid environments or in contact with chemicals. • Rigid structural elements such as brackets, bars, shafts and frames. • Automotive and aerospace industry.	Strong and stiff composite. Ideal for structural applications and metal replacement.	High heat resistance, up to 130 °C.	Tolerates exposure to corrosive chemicals. Composite material of choice for applications in humid environments.

Conclusion

In short, the properties of a filament should be at the forefront of your decision-making for any print job. A tensile test is an extremely informative way of retrieving analysis of the stress vs strain curve, ultimate tensile strength, elongation at break, and Young's modulus, allowing you to see which category your material fits into. For applications that will cause stress on the microscopic structure of an object, impact resistance should be considered. For withstanding high temperatures, look to the results from our Heat Deflection Temperature (HDT) test. Chemical resistance also needs to be taken into account, in the many forms that it comes in, whether it be resistance from acids, bases, water, or organic solvents.

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