A comparative study of mechanical behavior of ABS material based on UVC sterilization for medical usage

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Abstract This study aims to examine the mechanical properties of acrylonitrile butadiene styrene specimens using ASTM 638, 695, and 790. UVC radiation was also used as a sterilizing method. The fused deposition modeling of 3D-printed polymerize with 30 % filling was used to manufacture 30 specimens for tensile, compression, and bending. Half of the specimens were treated with UVC, whereas the other half were not. The chosen dosage of 13.5 J/cm² with an exposure time of 48 min corresponds to 3650 sterilization treatments or 10 years of sterilization. The average ultimate stress in the tensile test, compression test, and bending test was 34.5 ± 7.4, 25.4 ± 0.5, and 24.5 ± 2.1 Mpa, respectively. The analysis of variance test shows that UVC radiation has a demonstrable influence on tensile specimens, with a P-value of 0.012, which is less than the significance threshold of 0.05. Thus, the null hypothesis is rejected.

1. Introduction

Additive manufacturing (AM) has emerged as a common approach for producing various components. It uses layer-by-layer manufacturing technology, also known as three-dimensional (3D) printing. In contrast to traditional manufacturing processes that require forming (such as injection molding, bending, and stamping) and removing, 3D printing combines materials to build things. The advantages of AM over traditional manufacturing processes include energy savings, low environmental impact, and excellent scalability. Compared with traditional manufacturing processes, AM also achieves reduced waste material, manufacturing cycle time, and costs associated with low production runs and fast fabrication of geometrically complex parts. AM has been applied in a wide range of sectors, including automotive, electronics, aerospace, healthcare monitoring, construction, and fashion, because of its potential benefits [1-6]. Various AM processes have been used to print nearly anything, from little goods, such as toys and jewelry, to large ones, such as vehicles and houses [7].

Moreover, 3D printing has been extensively used to fabricate diverse structural components composed of ceramics [8], polymers [9], metals [10], glass [11], and multimaterials [12] using 3D models. In addition, 3D printing is less expensive and more adaptable than conventional production processes, such as machining, molds, and tooling. Furthermore, an evaluation at an early stage of product development may aid in preventing design flaws throughout the manufacturing process. Although 3D printing provides the advantages mentioned above, the quality, mechanical behavior, and performance of 3D-printed components rely on several variables.
Three-dimensional printing was first created to produce prototypes and limited quantities of completed things. However, it is currently utilized to produce finished goods. Therefore, the quality and mechanical behavior of these components have become important. In this context, research was conducted to establish the strength, structural integrity, and overall quality of additively manufactured components [13-18]. For example, in Ref. [18], fracture theories were applied for the first time to assess 3D-printed biomimetic materials. Thus, specimens were printed using the material jetting process, and a series of compact tension tests was performed in line with the appropriate standard to determine fracture toughness. The results demonstrated that the microstructure of the material is essential in toughening the composites. Given the reported results, designing microstructural components with the desired failure pattern is feasible.

A later study [19] showed that increasing the quantity of filler used enhances the tensile strength of acrylonitrile butadiene styrene (ABS) composites. ABS was filled with a range of CuO reinforcement loads and subjected to tensile loading to evaluate its strength. The gathered data suggested that tensile strength may be improved by up to 56 % in certain circumstances. A recent study [20] on the lifetime of 3D-printed mold components has been released. Three-dimensional printing was mainly employed to build a tool insert for injection molding. Before being used in the injection molding process, 3D-printed mold inserts are subjected to fast heat aging.

Additionally, researchers investigated the effect of sterilization on the mechanical behavior of 3D-printed ABS components by using acetone [21]. If a change occurs while the medical equipment is utilized at a hospital, the operation of the equipment may be affected. However, the data demonstrated that the sterilized specimens and those that were not sterilized have no statistically significant differences in strength and stiffness. ABS is a polymer that decomposes easily in acetone. Thus, it may be used to finish 3D-printed ABS components for various applications. Therefore, exploring the impact of post-processing on the mechanical behavior of 3D-printed components is critical.

UV irradiation is classified into three types: UVC (100-280 nm), UVB (280-315 nm), and UVA (315-400 nm). UVA and UVB radiation are utilized to treat skin ailments. The impact of narrowband (NB)-UVB light on people is lower than that of broadband (BB)-UVB light. The impact of NB-UVB on the body is also greater than that of other forms of UV treatment. Furthermore, NB-UVB light is safe for use in skin illnesses treatment [22, 28]. UVC radiation has sterilizing characteristics [29-31]. UVC irradiation at 254 nm is most efficient in killing bacteria, viruses, fungus, and even spores (in decreasing order of efficiency) by altering the structure of microorganisms’ DNA or RNA [11].

The current work aims to help the medical industry by investigating tensile, bending, and compression standard ASTM tests before and after the sterilization process using UVC lamps and ABS materials to decrease the infection rate, particularly during the COVID-19 pandemic.

2. Proposed approach

As shown in Fig. 1, the proposed approach is divided into five main sections. The first section is the fabrication method and the material selection. In this section, 3D printer and ABS material were selected because of reasonable cost, availability in the market, and many benefits of the 3D printer fabrication, which have been discussed in the Introduction. The second section involves the quantity and size of specimens. ASTM 638, ASTM 695, and ASTM 790 were selected as specimens’ sizes for tensile, compression, and bending tests, with 10 specimens for each ASTM. In the third part, the UVC lamp was used to sterilize half of the specimens. The other half of the group was not sterilized. In the fourth part of each test, an examination of the mechanical properties was performed. The last part is the decision-making part. This part checks if any significant difference exists between the sterilized and unsterilized specimens.

3. Material and methods

3.1 In fused deposition modeling (FDM) 3D printing, the processing parameters are important

Based on the American Society for Testing and Materials [30], 3D printing is divided into seven categories: (a) sheet lamination, (b) binder jetting, (c) material extrusion, (d) direct energy deposition, (e) powder bed fusion, (f) material jetting, and (g) vat photopolymerization. FDM is a commonly chosen technique in terms of 3D printing capabilities and flexibility. The FDM technique is a low-cost method of printing components onto a previously printed layer or building plates in a layer-by-layer fashion. The material is extruded via a nozzle that follows...
a predefined route to print the component onto a previously printed layer or build plates. The extruded material solidifies quickly and bonds to the surrounding material, allowing it to be used in constructing necessary components. FDM involves the deposition of successive layers accomplished through the extrusion of molten materials. Thus, it has many characteristics with other hot-processing manufacturing methods, such as AM. The FDM process is shown schematically in Fig. 2. Fiber deposition printing (FDM) is a well-known technique for producing structural components by using filaments made of polymers with various properties. Polymeric materials with varying degrees of flexibility, operating temperature, and hardness may be used. FDM comprises different materials, and the most popular materials include PLA and ABS. Short and long fiber-reinforced thermal polymers were also utilized as feedstock in certain studies to achieve the FDM process [31-33]. For example, carbon fiber-reinforced plastic composite specimens were produced in Ref. [33] by utilizing FDM, carbon fiber, and ABS. The samples were 3D printed by FDM in the TRONXY X5SA-500PRO machine. The filament specifications and properties and printing parameters are shown in Tables 1 and 2, respectively.

### 3.2 Geometrical data of the specimen production

Three specimen types for the tensile, compression, and bending tests were created with ABS. They were created using the 3D FDM method to ensure consistency. TRONXY X5SA-500PRO printer was used to produce all specimens for compression, tensile, and bending tests. This 3D printer is based on the fused filament fabrication technology, also referred to as FDM, even though the latter is sometimes considered a peculiarity of the Stratasys devices. According to ASTM D638 [34], ASTM D695 [35], and ASTM 690, the tensile, compression, and bending specimens have the typical dog bone shape, are parallelepiped-shaped cylinder with an appropriate length, and exhibit a rectangular shape, respectively.

#### 3.2.1 Tensile test specimen

The shapes and primary geometrical dimensions of the specimens used for tensile testing are shown in Fig. 2. The standard triangulation language (STL) format was used to transform the 3D CAD drawing. A suitable number of triangles were used to characterize each exterior and interior surface in this work. Converting the STL file into a G-code format was possible via the slicing procedure, which was necessary to send the primary instructions to the 3D printer for use in the manufacturing process. The printing direction was the x-direction, with an orientation sequence equal to 45 degrees, as shown in Fig. 3.

Printing 10 specimens from each test simultaneously was necessary to complete the manufacturing while ensuring consistency. Each test had three printing sets, and each test had 10 specimens. The possible consequences of this grouping for the geometrical and mechanical data are shown in the following sections. According to the primary printing data, the first layer thickness was 0.2 mm, the thickness of the subsequent layers was 0.1 mm, the number of perimeter beads was one, and the infill density was 30 % with a rectilinear fill pattern on the first layer. A 20 mm/s fill rate was used for the infill process.

Based on the geometrical data shown in Fig. 2, the nominal or target geometrical data are as follows: overall length of the specimen in the x-direction is 165 mm, length of the reduced

| Filament specifications and properties |
|--------------------------------------|
| Diameter (mm)                        | 1.75 mm |
| Density (g/cm³)                      | 1.04 g/cm³ |
| Tensile strength at yield (MPa)      | 43 Mpa |
| Elongation at break (%)              | 22 %    |

| Printing parameters                  |
|--------------------------------------|
| Infill ratio (%)                     | 30 %    |
| Nozzle diameter (mm)                 | 0.4     |
| Printing temperature                 | 245     |
| Printing speed (mm/s)                | 20 mm/s |
| Printing pattern rectangular         | Grid    |
| Layer height (mm)                    | 0.3     |

Fig. 2. A schematic of the FDM printing process.

Fig. 3. Dog bone specimen - the geometrical data (in millimeters).
section in the x-direction is 57 mm, the width of the reduced section in the y-direction is 13 mm, and thickness of the specimen in the z-direction is 3.2 mm.

The desired weight of 18.18 g was achieved by taking the volume of the specimen, as specified by the CAD model. It was multiplied by one for an infill density of one and by one for a mass density of 1.04 g/cm³ of ABS.

3.2.1.1 Specimen manufacturing

The actual geometrical data of each generated specimen were measured with a digital caliper. The weight of each specimen was calculated with a digital weight scale. Table 3 shows the actual measured data and the goal or values for the fabrication of 10 specimens. As shown in Fig. 4, these specimens were split into two families. Each family included five individuals. The first family was not exposed to UV radiation, whereas the second family would be exposed to UV radiation.

The accurate measurement of the length of the reduced section in the x-direction with the digital caliper was not feasible because of the existence of the curvature. In this instance, we specified only the goal value in the final line of the second column to proceed with our calculations. All of the goal values for each geometrical dimension were stated in the last line of the paragraph. The measured width of the decreased portion in the y-direction is given in the third column of this table. The values obtained from measuring the thickness of the specimens in the z-axis are shown in the fourth column. The weight of each specimen, as measured by the digital weight caliper, is listed in the fifth column. Finally, the last column provides the mass density obtained by dividing the weight by the target volume $V = 14.541$ cm³, as specified by the CAD software used for the CAD drawing (this choice was made because of the complexity of the geometry of the dog bone specimen; hence, determining its actual volume through true measurements is impossible).

After applying the tensile test, many key parameters were computed, including stress, strain, and modulus of elasticity, as illustrated by the following equation:

$$\sigma = \frac{P}{A_0}, \epsilon = \frac{L}{L_0}, \text{and } E = \frac{\sigma}{\epsilon}$$

where P is the load or force, $A_0$ is the initial area of the specimen, L is the final length of the specimen, and $L_0$ is the initial length of the specimen.

3.2.2 Compression test specimen

Based on the geometrical data shown in Fig. 5, the nominal or target geometrical data are as follows: the overall length of the specimen in the x-direction is 25.4 mm, and the diameter of the specimen is 12.7 mm. The manufacturer environment was the same as that mentioned earlier.

3.2.2.1 Specimen manufacturing

The actual geometrical data of each generated specimen was measured using a digital caliper. The weight of each specimen was calculated using a digital weight scale. Table 4 shows the actual measured data and the goal or values for the manufactured 10 specimens. As shown in Fig. 6, these specimens were split into two families. Each family included five individuals. The first family was not exposed to UV radiation.

$$\sigma = \frac{P}{A_0}, \epsilon = \frac{L}{L_0}, \text{and } E = \frac{\sigma}{\epsilon}$$

where P is the load or force, $A_0$ is the initial area of the specimen, L is the final length of the specimen, and $L_0$ is the initial length of the specimen.

Fig. 5. Parallelepiped-shaped specimen - geometrical data (in millimeters).

Fig. 6. ABS compression samples for mechanical testing: (a) five specimens were subjected to UV radiation; (b) five specimens were not subjected to UV radiation.
whereas the second family would be exposed to UV radiation.

### 3.2.3 Three-point bending test specimen

Based on the geometrical data shown in Fig. 7, the nominal or target geometrical data are as follows: the overall length of the specimen in the x-direction is 127 mm, width is 12.7 mm, and thickness of the specimen is 3.2 mm. The manufacturer environment was the same as that mentioned earlier.

#### 3.2.3.1 Specimen manufacturing

The actual geometrical data of each generated specimen was measured using a digital caliper, and the weight of each specimen was calculated with a digital weight scale. Table 5 shows the actual measured data and the goal or values for the manufactured 10 specimens. As shown in Fig. 8, these specimens were split into two families. Each family included five individuals. The first family was not exposed to UV radiation, whereas the second family would be exposed to UV radiation.

The machine was programmed to move at the rate of crosshead motion $\bar{\Omega}$, which was determined using Eq. (1). The following is extracted from the standard:

$$ R = \frac{ZL^2}{6h} = \frac{0.01 \times 52^2}{6 \times 3.2} = 1.4 \text{ mm/min} $$

(2)

where support span $L$ is 52 mm, the depth of beam $h$ is 3.2 mm, and the rate of strain of the outer fiber $z$ is 0.01 mm/min. The test was terminated when the distortion reached 5%.

### 3.3 UV irradiating chamber

For the UV radiation exposure, a locally made irradiating chamber with ten 20 W UV narrowband fluorescent lights were utilized. The lamps were placed in a straight line using a single plane. The irradiated area was 50x50 cm and placed approximately 20 cm below the lights’ installation plane, as shown in Fig. 9(a). The UV radiometer from ILT instruments was used to measure the irradiance levels across the irradiated region [36]. Fig. 9(b) depicts the layout of the three different specimens within the UV radiation chamber.
3.3.1 UV irradiation in viral inactivation

Ultraviolet light is electromagnetic radiation with a wavelength ranging from 100 nm to 400 nm. According to ISO 21348:2007, ultraviolet radiation is classified as UVA (315-400 nm), UVB (315-280 nm), UVC (200-280 nm), and vacuum UV–UVV (100-200 nm). As the wavelength lowers, the energy of each photon rises, and the interaction with various organic and inorganic substances changes. UVA radiation causes skin tanning and long-term damage. UVB may be used to treat skin conditions, such as psoriasis. UV light is absorbed by the atmosphere. Thus, it is useless in an environmental situation. UVC is the most intriguing for antimicrobial applications because it is the most efficient at inactivating both bacteria and viruses.

UVC radiation in the 250-280 nm range deactivates bacteria, viruses, and other organisms by destroying their DNA. UVC light can infiltrate microorganism cells and alter the structure of DNA molecules by deleting the genetic information inside the DNA, as shown in Fig. 10. Thus, the bacteria lose their capacity to reproduce and are eliminated, making them dormant and no longer hazardous. UV's germicidal nature makes it ideal for treating bacteria that become exceedingly resistant to chemical disinfectants, given that they cannot build a tolerance to UV radiation.

3.3.2 Calculation of the exposure time

Ten 20 W UVC lamps were used in the cabinet with ultraviolet light. The average distance between the lamps of 4.74 mw/cm² and the sample was 10 cm, according to the cabinet with ultraviolet light. The dosage was estimated to be 13.5 J/cm² when the exposure duration was equivalent to 48 min. Based on the previous studies, 3.7 mJ/cm² at 254 nm is the dose value necessary to obtain the inactivation of SARS-COVID.

The following equation may be used to explain the process of determining the duration of exposure on irradiance or lamp’s intensity and the dosage base:

$$Dose\left(\frac{mJ}{cm^2}\right) = \text{Irradiance}\left(\frac{mw}{cm^2}\right) \times \text{time}(s)$$

$$13500 \left(\frac{mJ}{cm^2}\right) = 4.74 \left(\frac{mw}{cm^2}\right) \times \text{time}(s) \quad .$$  (3)

time = 47.5 min - 48 min

3.4 Analysis of variance (ANOVA) test

If statistically significant differences exist between the means of three or more independent (unrelated) groups, the one-way ANOVA is employed. The one-way ANOVA examines the means of the groups being focused to determine whether any of them are statistically and substantially different from one another. This test examines the null hypothesis in particular.

$$H_0 : \mu_1 = \mu_2 = \mu_3 = \ldots = \mu_i.$$  (4)

In the null hypothesis for one-way ANOVA, the group mean and k are the number of groups.

ANOVA examines differences in group means by dividing the entire variance in the data into two components: variation between groups and variation within the group.

ANOVA divides the total sum of squares (SST), which is equal to the sum of squares between-groups (SSR) and the sum of squared within groups (SSE).

$$\sum_{ij} (y_{ij} - \bar{y})^2 = \sum_{i} n_i (\bar{y}_i - \bar{y})^2 + \sum_{i} \sum_{j} (y_{ij} - \bar{y}_i)^2 \quad .$$  (5)

where $\bar{y}_{ij} - \bar{y}$ is the variation between groups, $\bar{y}_i - \bar{y}$ is the variation within the group, and $n_i$ is the sample size of $\beta$ group ($\beta = 1, 2, 3, \ldots k$).

Then, the variance between groups was compared with the variation within them using ANOVA. If the ratio of between-group variance to within-group variation is considerably large, then the group means are significantly different. This outcome may be determined using a test statistic using an F-distribution and degrees of freedom ($k - 1, N - k$):

$$F = \frac{SSR/k - 1}{SSE/(N - k)} = \frac{MSR}{MSE} \sim F_{k-1, N-k}$$  \hspace{1cm} (6)

where MSR is the mean squared treatment, MSE denotes the mean squared error, $k$ denotes the number of groups, and $N$ denotes the total number of observations. If the F-statistic p-value is less than the significance threshold, the test rejects the null hypothesis that all group means are equal and concludes that at least one group mean differs from the others. The most typical thresholds of significance are 0.05 and 0.01.

3.5 Energy dispersive X-ray analysis

Energy dispersive X-ray (EDS) microanalysis is an elemental analysis method related to electron microscopy that generates distinctive X-rays indicating the existence of elements present in specimens. Many researchers and physicians employ EDS microanalysis in many biological domains. However, the majority of the scientific community is unaware of its potential uses.

Another validation tool that can be added to verify the results...
is energy dispersive x-ray analysis (EDS). It is a technique for analyzing the element compositions in any given material. The EDS method is used to determine the energy levels that correlate to the presence of carbon and oxygen [37]. Additionally, the presence of heat and light (particularly UV) accelerates degradation and oxidation processes, and polymers exposed to UV radiation become increasingly brittle on prolonged exposure [38]. Brucker xflash 6130 with cross-sectional SEM image (magnification 925x; voltage 20 KV; WD 15 mm) was used.

4. Results and discussions

4.1 Tensile test

In this experiment, the ASTM D638 technique for classical polymer testing was used. This technique is defined in detail in the standard. This standard specifies the use of a dog bone form specimen and constant speed. Thus, a 5 mm/min specimen and a frequency of 20 Hz were selected in the data acquisition.

The tensile tests were performed on the SHIMADZU machine, which was fitted with a 5 kN load cell. Both the tensile load $P[N]$ and upper crossbar displacement $D_L$ were recorded and saved.

Figs. 11 and 12 depict the stress–strain curves obtained from the tensile tests performed on the first group of five specimens not subjected to UVC radiation and those obtained from the tensile tests performed on the second group of five specimens subjected to UVC radiation, respectively. The tensile test clearly showed the yield force, yield stress, yield strain, ultimate force, ultimate stress, ultimate strain, break force, break stress, and break strain. This test also showed the break force, break stress, and break strain. According to the definition of the linear elastic young modulus, it is the coefficient of proportionality between stresses and deformations in the linear elastic region. The ultimate tensile strength of a specimen is the greatest stress value that this specimen can tolerate before breaking on a stress-strain curve. Stress-strain curves are graphed and characterized as having the maximum value reached by the stress at a certain point.

The yield force, yield stress, and yield strain, as well as the ultimate force, ultimate stress, and ultimate strain, can be extracted from the two preceding figures. Other significant characteristics that can be extracted from the tensile test include the brake force, break stress, and breaking strain. Table 6 presents a brief overview of the proposed values, enabling researchers to compare these values easily. The group that was not subjected to UVC radiation was group A, and the other

Table 6. ASTM 638 tensile test parameters.

| Specimen number | Yield force (kg) | Yield stress (Mpa) | Yield strain (%) | Ultimate force (kg) | Ultimate stress (Mpa) | Ultimate strain (%) | Break force (kg) | Break stress (Mpa) | Break strain (%) |
|-----------------|-----------------|-------------------|----------------|--------------------|----------------------|-------------------|-----------------|------------------|-----------------|
| 1 (no UVC dose) | 95.4            | 22.6              | 5.66           | 95.4               | 22.6                 | 5.66              | 95.4            | 22.6             | 5.66            |
| 2 (no UVC dose) | 92.9            | 21.7              | 5.41           | 92.9               | 21.7                 | 5.41              | 92.9            | 21.7             | 5.41            |
| 3 (no UVC dose) | 95.1            | 22.2              | 6.19           | 95.1               | 22.2                 | 6.19              | 95.1            | 22.2             | 6.19            |
| 4 (no UVC dose) | 85.9            | 20.3              | 4.76           | 85.9               | 20.3                 | 4.76              | 85.9            | 20.3             | 4.76            |
| 5 (no UVC dose) | 165             | 38.1              | 6.14           | 165                | 38.1                 | 6.14              | 165             | 38.1             | 6.14            |
| Average±std     | 107±32.7        | 25±7.4            | 5.6±0.6        | 107±32.7           | 25±7.4               | 5.6±0.6           | 107±32.7        | 25±7.4           | 5.6±0.6         |
| 1 (UVC dose)    | 151             | 35.6              | 4.93           | 151                | 35.6                 | 4.93              | 151             | 35.6             | 4.93            |
| 2 (UVC dose)    | 91.1            | 21.8              | 4.98           | 91.1               | 21.6                 | 4.98              | 91.1            | 21.6             | 4.98            |
| 3 (UVC dose)    | 167             | 39.1              | 6.15           | 167                | 39.1                 | 6.15              | 167             | 39.1             | 6.15            |
| 4 (UVC dose)    | 164             | 37.5              | 6.28           | 164                | 37.5                 | 6.28              | 164             | 37.5             | 6.28            |
| 5 (UVC dose)    | 164             | 38.9              | 6.18           | 164                | 38.9                 | 6.18              | 164             | 38.9             | 6.18            |
| Average±std     | 147.4±32.1      | 34.5±7.4          | 5.7±0.7        | 147.4±32.1         | 34.5±7.4             | 5.7±0.7           | 147.4±32.1      | 34.5±7.4         | 5.7±0.7         |

Fig. 11. Strain-stress for five specimens of ABS material not subjected to UVC radiation.

Fig. 12. Strain-stress for five specimens of ABS material subjected to UVC radiation.
The most significant tensile test parameters may be stated as follows: (a) yield force, (b) yield stress, (c) yield strain, (d) ultimate force, (e) ultimate stress, (f) ultimate strain, (g) break force, (h) break stress, and (i) break strain. In this case, the yield forces for group B are larger than those for group A; the average value for group A is 107±32.7 kg, whereas the average value for group B is 147.4±32.1 kg. The yield stress for group B is higher than that for group A; the average value for group A is 25±7.4 Mpa, whereas the average value for group B is 34.5±7.4 Mpa. Compared with group A, group B seems to possess a near yield strain; the average value for group A is 5.6 %±0.6 %, whereas the average value for group B is 5.7 %±0.7 % on the yield strain scale. The values of ultimate force, ultimate stress, and ultimate strain were the same as those of the yield force, yield stress, and yield strain, respectively. Moreover, the values of brake force, break stress, and breaking strain were the same as those of the yield force, yield stress, and yield strain, respectively.

Therefore, no plastic region existed. The only area under the curve was an elastic region. The ABS material is brittle. Fig. 13 depicts the form of groups A and B samples after they have been broken, indicating that both groups are brittle materials. Fig. 13(a) represents the shape of the group A sample, whereas Fig. 13(b) represents the shape of the group B sample. The yield stress parameter of the group treated with UVC radiation was affected. The yield stress of group B was larger than that for group A, indicating that UVC doses have a favorable impact on the yield stress parameter but have no influence on other mechanical characteristics.

### 4.2 Compression test

This compression test used the ASTM D695-15 technique for classical polymer testing, which is detailed in the standard. This standard specifies the use of a dog bone form specimen and constant speed. Thus, a 5 mm/min specimen and a frequency of 20 Hz were employed in the data collection.

This test was also performed on the SHIMADZU machine, which was equipped with a 5 kN load cell. During the compression tests, the compression load P[N] and the displacement DL (in [mm]) of the upper crossbar were recorded and saved.

| Specimen number | Ultimate force (kg) | Ultimate stress (Mpa) | Displacement (mm) |
|-----------------|---------------------|-----------------------|-------------------|
| 1 (no UVC dose) | 318.21              | 25.11                 | 2.71              |
| 2 (no UVC dose) | 325.14              | 25.82                 | 3.15              |
| 3 (no UVC dose) | 331.80              | 26.22                 | 3.42              |
| 4 (no UVC dose) | 328.08              | 26.47                 | 3.11              |
| 5 (no UVC dose) | 315.18              | 24.99                 | 3.11              |
| Average±std     | 323.7±6.9           | 25.7±0.7              | 3.1±0.3           |
| 1 (UVC dose)    | 329.82              | 26.11                 | 3.5               |
| 2 (UVC dose)    | 318.88              | 25.44                 | 3.11              |
| 3 (UVC dose)    | 319.03              | 25.58                 | 3.24              |
| 4 (UVC dose)    | 317.68              | 25.35                 | 3.32              |
| 5 (UVC dose)    | 312.38              | 24.69                 | 2.98              |
| Average±std     | 319.6±6.4           | 25.4±0.5              | 3.2±0.2           |

Compression tests were performed on group A and group B. The position-force curves obtained from the compression tests performed on group A are shown in Fig. 14, and those for group B are illustrated in Fig. 15.

The information on the ultimate force, ultimate stress, and displacement can be obtained using the ASTM 695 compression test. Table 7 provides a high-level summary of the recommended values, allowing researchers to compare these values straightforwardly. The group that was not exposed to UVC radiation is group A, whereas the other group is group B.

The following are the most important compression test parameters in order of importance. Ultimate forces have three types: (a) ultimate force, (b) ultimate stress, and (c) displacement. The maximum force of group B is quite close to that of group A in this situation; the average value for group A is 323.7±6.4 kg, whereas the average value for group B is 319.6±6.4 kg. Compared with the ultimate stress for group A, the ultimate stress for group B reveals similar values; the average value for group A is 25.7±0.7 Mpa, whereas the average...
value for group B is 25.4±0.5 Mpa. According to the displacement scale, group B seems to have a similar displacement to group A; the average value for group A is 3.1±0.3 mm, whereas the average value for group B is 3.23±0.2 mm on the displacement scale.

The ultimate stress in the ASTM 695 was very similar to the ultimate stress in the ASTM 638 in the group that was not subjected to UVC radiation; the average ultimate stress in the tensile test is 25±7.4 Mpa, whereas the average ultimate stress in the compression test is 25.7±0.7 Mpa in the tensile test. Furthermore, a significant difference exists between the ultimate stress in the ASTM 695 and that in the ASTM 638 in the group subjected to UVC radiation; the average ultimate stress in the tensile test is 34.5±7.4 Mpa, whereas the average ultimate stress in the compression test is 25.4±0.5 Mpa.

The ultimate stress parameter in the tensile test was altered when exposed to UVC radiation. However, the ultimate stress parameter in the compression test was unaffected, as shown in Fig. 16.

4.3 Three-point bending test

The ASTM 790 procedure for classical polymer testing was used in this three-point bending test, which is fully described in the standard. The machine was programmed with a crosshead motion (R) rate equal to 1.4 mm/min.

The three-point bending tests were performed in three different directions for groups A and B. Figs. 17 and 18 depict the stress–length curves obtained from the bending tests performed on groups A and B, respectively.

The ASTM 790 three-point bending test may provide information on the modulus of elasticity, ultimate force, and ultimate stress. Table 8 shows a high-level overview of the suggested values, enabling researchers to compare these values in an easy-to-understand manner. Group A refers to the group not exposed to UVC radiation, and group B refers to the group exposed to UVC radiation.

The following are the most important bending test parameters in order of importance. Three types exist: (a) modulus of elasticity, (b) ultimate force, and (c) ultimate stress. The maximum force of group B is quite close to that of group A in this situation; the average value for group A is 2.14±0.2 kg, whereas the average value for group B is 2.04±0.2 kg. The ultimate stress for group B is similar to that for group A; the average value for group A is 24.5±2.1 Mpa, whereas the average value for group B is 24.7±2.8 Mpa. According to the modulus of elasticity scale, the modulus of elasticity of group B seems to be similar to that of group A; the average value for group A is 967.4±47 Mpa, whereas the average value for group B is 1043.2±40 Mpa on the modulus scale.

The ultimate stress in the ASTM 695 was very similar to that in ASTM 638 and ASTM 790 in the group not subjected to UVC radiation; the average ultimate stress in the tensile test is

| Specimen number | Modulus of elasticity (Mpa) | Ultimate force (kg) | Ultimate stress (Mpa) |
|-----------------|-----------------------------|--------------------|----------------------|
| 1 (no UVC dose) | 891                         | 2.15               | 25.4                 |
| 2 (no UVC dose) | 975                         | 2.34               | 26.5                 |
| 3 (no UVC dose) | 1020                        | 2.17               | 24.7                 |
| 4 (no UVC dose) | 980                         | 1.89               | 21                   |
| 5 (no UVC dose) | 971                         | 2.16               | 24.9                 |
| Average±std     | 967.4±47                    | 2.14±0.2           | 24.5±2.1             |
| 1 (UVC dose)    | 1090                        | 2.19               | 28                   |
| 2 (UVC dose)    | 1010                        | 1.86               | 21.7                 |
| 3 (UVC dose)    | 1050                        | 2.17               | 26.9                 |
| 4 (UVC dose)    | 1070                        | 1.9                | 22.1                 |
| 5 (UVC dose)    | 996                         | 2.09               | 24.6                 |
| Average±std     | 1043.2±40                   | 2.04±0.2           | 24.7±2.8             |

Fig. 16. The shape of samples after the break: (a) five specimens of ABS material not subjected to UVC radiation; (b) five specimens of ABS material subjected to UVC radiation.

Fig. 17. Stress-length curve for five specimens of ABS material not subjected to UVC radiation.

Fig. 18. Stress-length curve for five specimens of ABS material subjected to UVC radiation.
25±7.4 Mpa, the average ultimate stress in the compression test is 25.7±0.7 Mpa in the tensile test, and the average ultimate stress in the compression test is 24.5±2.1 Mpa in the bending test. Furthermore, a significant difference exists between the ultimate stress in ASTM 695, ASTM 790, and ASTM 638 in the group subjected to UVC radiation; the average ultimate stress in the tensile, compression, and bending tests is 34.5±7.4 Mpa, 25.4±0.5 Mpa, and 24.5±2.1 Mpa, respectively.

The ultimate stress parameter in the tensile test was altered when the specimens were exposed to UVC radiation. However, the ultimate stress parameter in the compression and bending test was unaffected, as shown in Fig. 19.

### 4.4 ANOVA test

The review of all mechanical parameters in tensile, compression, and bending tests indicates that ultimate stress is the common mechanical parameter in the three tests. Therefore, the ANOVA test discriminated the effects of UV radiation in the three tests based on ultimate stress. Six groups were selected for the ANOVA test: tensile ultimate stress before UV, tensile ultimate stress after UV, compression ultimate stress before UV, compression ultimate stress after UV, bending ultimate stress before UV, and bending ultimate stress after UV. The ANOVA test was chosen as the validation tool. The ANOVA test was also used to determine whether a significant difference exists between the ultimate stress values for tensile, compression, and bending tests in groups treated with UVC radiation and the values in groups not treated with UVC radiation. The null hypothesis indicates that all means are equal or that no significant difference exists. Table 9 shows all the ultimate stresses for tensile, compression, and bending tests for the three groups treated with UVC radiation and those that were not.

![Fig. 19](image1.png)

![Fig. 19](image2.png)

![Fig. 20](image3.png)

![Fig. 20](image4.png)

Table 9. Ultimate stresses for tensile, compression, and bending tests for groups treated with UVC radiation and those not treated with UVC radiation.

| Tensile before UV | Tensile after UV | Compression before UV | Compression after UV | Bending before UV | Bending after UV |
|------------------|-----------------|-----------------------|---------------------|------------------|-----------------|
| Group 1          | Group 2         | Group 3               | Group 4             | Group 5          | Group 6         |
| 22.6             | 35.6            | 25.11                 | 26.11               | 25.4             | 28              |
| 21.7             | 21.6            | 25.82                 | 25.44               | 26.5             | 21.7            |
| 22.2             | 39.1            | 26.22                 | 25.58               | 24.7             | 26.9            |
| 20.3             | 37.5            | 26.47                 | 25.35               | 21               | 22.1            |
| 38.1             | 38.9            | 24.99                 | 24.69               | 24.9             | 24.6            |

The ANOVA test showed that a clear significant difference exists between group 2 and all other groups, as shown in Figs. 20(a) and (b). Fig. 20(a) describes the box plot, whereas Fig. 20(b) describes multiple comparison test, which reflects that a clear effect was observed on the tensile specimens after being treated with UVC radiation. The P-value of the ANOVA test is 0.012, which is less than the significant level of 0.05. Thus, the null hypothesis is rejected. In particular, if P-value < 0.05, the
The null hypothesis is rejected, and if P-value > 0.05, the null hypothesis is accepted (null hypothesis means that all averages from all groups are equal).

4.5 Energy dispersive X-ray analysis

The second validation method is EDS analysis. The energy spectrum of the tensile test specimens was selected to determine where the peak energies are used before and after UV sterilization to calculate the concentration of a certain element in a sample. Each element has a distinct atomic structure, resulting in a distinct set of peaks on its electromagnetic emission spectrum.

As shown in Fig. 21, the spectrum of the EDS analysis for tensile test specimens before and after sterilization illustrated that carbon (in red color) is more dominant than oxygen (in green color) before and after UV sterilization. The decrease in the carbon mass and increase in oxygen mass appeared after sterilization degradation and oxidation, as shown in Table 10. Therefore, EDS analysis can be another validation method that shows degradation and oxidation. It showed that the material was more brittle after the sterilization process than it was before.

### Table 10. Mass element parameter for EDS analysis before and after sterilization.

| Element | Before sterilization | After sterilization |
|---------|----------------------|---------------------|
|         | Mass (%) | Atom (%) | Mass (%) | Atom (%) |
| Carbon  | 77.69    | 82.27     | 72.78    | 78.08    |
| Oxygen  | 22.31    | 17.73     | 27.22    | 21.92    |

Fig. 21. EDS analysis before and after sterilization: (a) spectrum for tensile test specimen before sterilization; (b) spectrum for tensile test specimen after sterilization.

5. Conclusions

ABS is a promising material in the medical manufacturing industry because it can withstand exposure to ultraviolet C radiation for an extended amount of time without deteriorating. According to different perspectives, the use of UVC radiation in the tensile specimens affects the tensile specimens. Given the result of the current investigation, the medical industry sectors are advised to use ABS material in compression and bending applications if their fabrications are disinfected with UVC radiation for an extended period. ANOVA test was used to determine whether a significant difference exists between the ultimate stress values for tensile, compression, and bending tests in groups treated with UVC radiation and those in groups not treated with UVC radiation. The null hypothesis indicates that all means are equal.

Acknowledgments

The authors extend their appreciation to the Deanship of Scientific Research at Majmaah University for funding this study under Project number R-2022-79.

The authors would also like to express their sincere gratitude to the Biomedical Engineering Department, Faculty of Engineering, Misr University for Science and Technology, Egypt, for providing guidance throughout this investigation.

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