

Investigation of the mechanical performance of heat-treated ABS and recycled ABS materials

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ABSTRACT

Three-dimensional printing plays a key role in rapid medical manufacturing, yet the resulting plastic waste poses environmental challenges. Combining additive manufacturing with mechanical recycling offers a sustainable circular economy solution. In this study, specimens were produced from acrylonitrile butadiene styrene (ABS) and recycled acrylonitrile butadiene styrene (Re-ABS) materials obtained through the mechanical recycling of waste prints resulting from production errors, using the Fused Deposition Modelling (FDM) method, one of the 3D printing technologies. The specimens were manufactured with different infill rates (25%, 50% and 75%) in two different infill pattern orientations (Vertical and Horizontal Truss). After production, heat treatment was applied to the specimens at temperatures of 90, 110, and 130 °C, and the effects of heat treatment on mechanical and surface properties were experimentally investigated. All specimens underwent tensile strength and three-point bending tests, as well as surface roughness measurements, hardness tests, and scanning electron microscope (SEM) analyses.

The results obtained indicate that the most influential parameter on mechanical properties is the infill rate. As the fill ratio increases, strength and hardness increase while surface roughness decreases. Heat treatment has improved mechanical performance, particularly in Re-ABS samples, while the infill pattern orientations have had a secondary effect.

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1. INTRODUCTION

Additive manufacturing technologies have attained a strategic position in the manufacturing industry in recent years due to their ability to produce complex geometries, offer design freedom, and significantly reduce production waste. Unlike traditional manufacturing methods, in additive manufacturing processes, parts are produced layer by layer based on digital three-dimensional models. This approach both shortens prototyping time and enables the low-cost production of functional parts. For this reason, additive manufacturing is widely used in many sectors, including automotive, aerospace, biomedical, energy, and defence industries [1]-[4]. Among additive manufacturing technologies, Fused Deposition Modelling (FDM) is one of the most preferred methods due to its ease of use, low equipment cost, and the widespread availability of desktop printers. In FDM technology, thermoplastic filament is melted at a specific temperature, extruded through a nozzle, and deposited layer by layer to form the final part. However, this layered structure leads to anisotropic behaviour in terms of mechanical properties, and the performance of the produced parts becomes largely dependent on the printing parameters [5]-[7]. Among the thermoplastic materials commonly used in FDM production, acrylonitrile butadiene styrene (ABS) stands out. ABS is frequently preferred in engineering applications due to its high impact resistance, good toughness properties, and thermal stability. In addition, ABS is widely used in the biomedical field for the production of medical device housings, laboratory equipment, medical prototypes, and customised assistive devices. Its mechanical strength and mouldability make ABS a suitable material for functional medical applications. However, the fact that ABS is a fossil-based polymer and that significant amounts of waste are generated during its production process poses a significant problem in terms of environmental sustainability. In particular, failed prints, support structures, and end-

of-life parts constitute the main sources of 3D printer waste [8], [9]. The increase in plastic waste resulting from the widespread adoption of 3D printing technologies has led researchers to explore mechanical recycling methods. Mechanical recycling offers an environmentally advantageous approach by reducing raw material and energy consumption. The fact that 3D-printed ABS components used in biomedical applications become waste after use makes the controlled and safe recycling of this waste even more important. The recovery of medical plastic waste is considered a critical requirement in terms of both reducing the environmental burden and developing sustainable health technologies. However, breaks in polymer chains during the recycling process can lead to a decrease in average molecular weight and, consequently, a decline in mechanical properties. This situation calls into question the reliability of recycled ABS (Re-ABS) filaments in structural applications [10]. In the literature, there are numerous studies aimed at optimising production parameters to improve the mechanical performance of recycled filaments. In particular, the infill rate, layer thickness, and production orientation play a decisive role in the tensile, flexural, and impact strength of parts produced by FDM. Increasing the infill rate improves load transfer by reducing the void ratio in the internal structure, while layer thickness and production orientation directly affect the interlayer bonding mechanism [11]-[13]. However, a significant portion of existing studies have focused on PLA filaments, and the mechanical response of recycled ABS filaments to production parameters has been addressed in only a limited number of studies. In particular, how the anisotropic behaviour dependent on the production direction changes with the recycling process has not been sufficiently clarified in the literature. This situation creates an important research gap in terms of the reliable use of recycled filaments in engineering applications [14]. In recent years, an increasing number of studies have reported on the effects of post-production heat treatments (annealing/heat treatment) applied to improve the mechanical properties of thermoplastic materials produced using the FDM method. Heat treatment promotes interlayer diffusion by increasing polymer chain mobility, reduces internal stresses, and improves interlayer bonding quality. It has been reported that thermal treatment applied at appropriate temperature ranges, particularly in ABS materials, can increase tensile and flexural strength, but that excessive temperatures can cause deterioration in dimensional stability and surface quality. In recycled ABS filaments, it is stated that heat treatment can partially improve the polymer chain structure and interlayer bonding weakened during the recycling process, thereby compensating for mechanical performance losses. In this context, evaluating thermal treatment parameters alongside printing parameters such as infill pattern orientations and fill rate is of great importance for increasing the usability of Re-ABS materials in engineering and biomedical applications [15], [16]. In this study, the mechanical behaviour of ABS and recycled ABS (Re-ABS) specimens produced using the FDM method was experimentally investigated. The specimens were produced considering different infill rates and infill pattern orientations; the effects of post-production heat treatment (annealing) applied at different temperatures on the mechanical properties were systematically evaluated. The role of heat treatment on interlayer bonding quality, reduction of internal stresses, and anisotropic mechanical behaviour depending on the infill pattern orientations was analysed in detail. Furthermore, the extent to which thermal treatment can compensate for the degradation occurring in polymer chains during the recycling process has been revealed. The results obtained are intended to contribute to increasing the usability of recycled ABS filaments in engineering and biomedical applications, as well as to the development of sustainable and environmentally friendly 3D printing applications.

2. METHOD

2.1. Material and Recycling Steps

In this study, ABS PLUS filaments manufactured by ELAS 3B were used as raw material in the production of ABS specimens. Re-ABS specimens, on the other hand, were manufactured from filaments obtained by recycling parts that were produced using the same ABS PLUS filaments with a 3D printer but could not be used due to production errors. With this approach, the aim was to comparatively examine the mechanical behaviour of the original and recycled ABS materials. During the recycling process, faulty or waste parts produced after 3D printer manufacturing were systematically collected and subjected to pre-treatment to remove dirt, grease, and printing residues from their surfaces. In this context, the printing waste was washed in an aqueous solution containing 1% NaOH and 3% active surface cleaner at 85 °C under industrial conditions. Following the cleaning process, the materials were dried under vacuum to minimise moisture content. The dried waste was processed in a Rondol Microlab twin-screw extruder with a screw speed of 60 rpm and a feed rate of 20 L/D for the purpose of producing recycled filament. The geometric design of the test specimens was carried out using SolidWorks/Premium 2022 CAD software, and the models were saved in STL format. Subsequently, the necessary process parameters for the production of the specimens were determined using UltiMaker Cura 5.10.0 slicing software, and the specimens were prepared for the printing process. All specimens from the obtained ABS and Re-ABS filaments were produced using the FDM (Fused Deposition Modelling) method with a Creality-branded Ender-3 V3 Creality 3D Printer. The produced specimens were subjected to heat treatment at temperatures of 90, 110, and 130 °C for 1 hour using a WiseVen

brand fan oven (operating range: ambient temperature +5 °C – 250 °C). After heat treatment, the specimens were cooled in a controlled manner in the oven and prepared for testing to examine their mechanical properties. The specimens were positioned in two different configurations to investigate the effect of the production direction and parameters on mechanical properties. Accordingly, the specimens were named vertical truss and horizontal truss. Figures 1 (a) and (b) show the shapes and dimensions of the specimens used in the tensile and three-point bending tests, respectively. Figures 2 (a) and (b) schematically present the axis directions of the specimens belonging to the vertical and horizontal truss configurations. All production parameters used in the study and the mechanical properties of the ABS filament are given in Table 1 and Table 2, respectively.

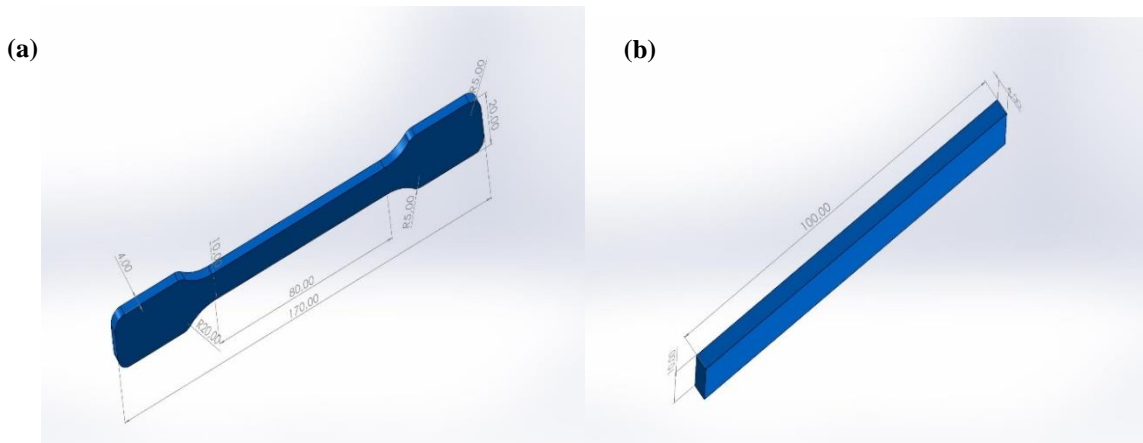


Figure 1. Shapes and dimensions of (a) tensile and (b) three-point bending specimens.

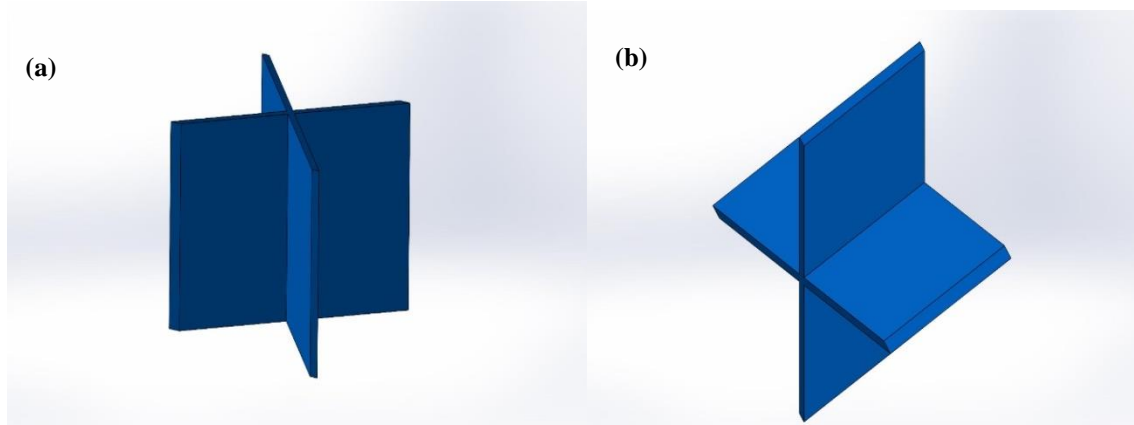


Figure 2. Axis directions of the specimens (a) vertical truss (b) horizontal truss.

Table 1. Production parameters used.

Material	Infill Pattern Orientation	Heat Treatment, °C	Infill Rate, %
ABS	Vertical Truss	90	25
			50
			75
		110	25
			50
			75
	Horizontal Truss	90	25
			50
			75
		110	25
			50
			75

		130	50
			75
			25
			50
			75
			25
Re-ABS (Recycled)	Vertical Truss	90	50
			75
			25
		110	50
			75
			25
	Horizontal Truss	90	50
			75
			25
		110	50
			75
			25
130	50		
	75		
	25		

Table 2. Mechanical properties of the ABS filament used.

Property	Value
Density, g/cm ³	1.04
Tensile Strength, Mpa	43
Bending Strength, Mpa	66
Elongation at Break, %	22
Printing Temperature, °C	220-260

2.2. Characterization Studies

In this study, specimens were positioned on the build plate in two different infill pattern orientations using ABS and Re-ABS filaments, and production was carried out accordingly. All necessary mechanical tests were performed to reveal the effect of the infill pattern orientations and parameters on material behaviour, and details of the experiments conducted are presented below.

2.2.1. Mechanical Tests

Tensile strength tests were prepared in accordance with the specimen geometries specified in the ISO 527-1 standard, as appropriate for the purpose of the study. During the tests, the tensile speed was kept constant at 5 mm/min, and all measurements were performed at an ambient temperature of 25 °C. For the three-point bending tests, specimens compliant with the ISO 178 standard were used. In these tests, the distance between supports was set to 64 mm, the bending speed was selected as 2 mm/min, and the tests were again performed at an ambient temperature of 25 °C. All tensile strength and three-point bending tests were performed using a Zwick/Roell brand testing machine. In surface roughness measurements, tensile test specimens that retained their integrity after mechanical testing were used. Measurements were performed on the specimen surfaces shown in Figure 1(a), and the Ra (arithmetic mean roughness) parameter was used as the basis for evaluating surface quality. All measurements were performed at an ambient temperature of 25 °C, and the average of the values obtained from five different points on each specimen was taken. Surface roughness measurements were performed using a Mitutoyo SurfTest SJ-210 model device, and the results were analysed using the ‘Surface Roughness Tester SJ-210/310/410’ software. Hardness tests were conducted in accordance with the ASTM D2240-15 standard. Shore D hardness measurements were performed on the specimens to be used in tensile tests prior to the tensile test. Hardness measurements were made using a PCE-DD D digital Shore D durometer, employing a conical steel needle with a tip radius of 0.1 mm. In this study, for all tensile, three-point bending, surface roughness, and hardness tests performed, measurements were taken on 5 specimens for each production parameter, and the arithmetic mean of the results obtained was taken for evaluation. Figure 3 shows some of the equipment and specimens used in the tests.

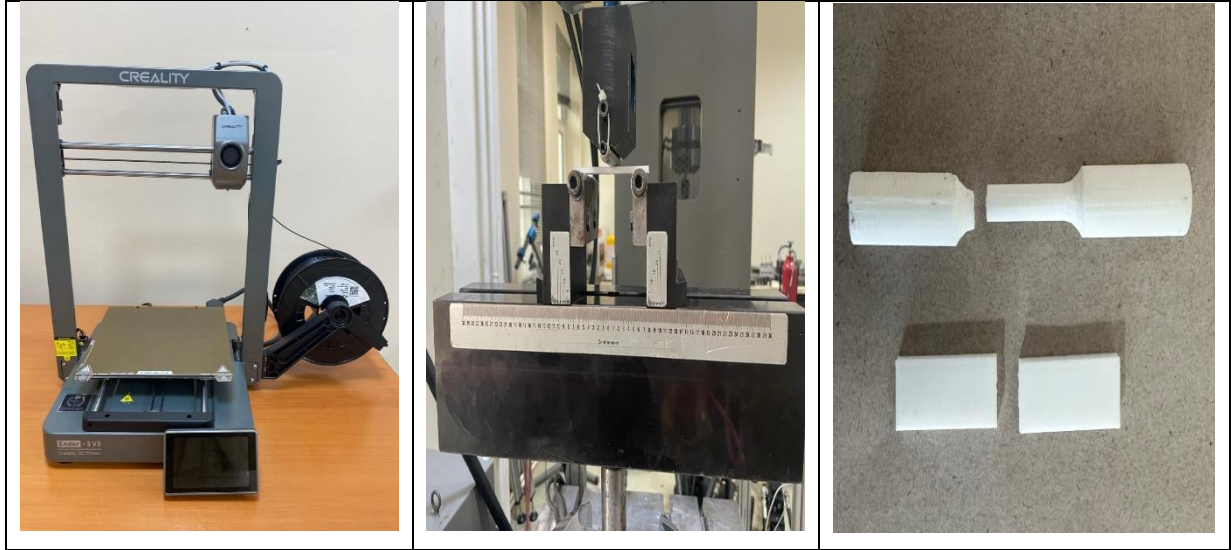


Figure 3. Some of the equipment and specimens were used in the experiments.

2.2.2. SEM Analysis

In this study, the fractured surfaces of the produced ABS and Re-ABS specimens were examined using scanning electron microscopy (SEM) to investigate the fracture mechanisms that occurred after the experiments. The microstructures of the original and recycled ABS specimens were examined at different magnifications ranging from 100x to 1000x using the FEI QUANTA 450 FEG ESEM device located at the Polymer Technologies and Composite Application and Research Centre of Istanbul Arel University (Arel POTKAM). In the SEM analyses, the specimens were evaluated under two separate groups, considering the material type (ABS and Re-ABS) and infill pattern orientations.

3. RESULTS AND DISCUSSION

The results of tensile, three-point bending, surface roughness, hardness, and SEM analyses conducted on standard tensile and three-point bending specimens produced from filament are evaluated in this section. Using the data obtained, average values for the specimens were calculated, and the relevant curves were generated.

3.1. Tensile Test Results

The tensile test is a widely used method for determining the mechanical properties of materials, which helps to ensure that finished products are manufactured to a high standard and fit for purpose [17]. In order to present the tensile test results of the ABS and Re-ABS specimens in a clearer and more comparable manner after the test, the percentage change rates in the tensile strength and elongation at break values were calculated, and these data were presented in graphs. Sub-sections (a), (b), and (c) of Figure 4 present graphical representations of the tensile strength test results for ABS and Re-ABS specimens, respectively, based on the infill rate, heat treatment, and infill pattern orientation. In contrast, Figure 5 (a), (b), and (c) show the graphical distributions of the elongation at break test results for ABS and Re-ABS specimens according to the same parameters.

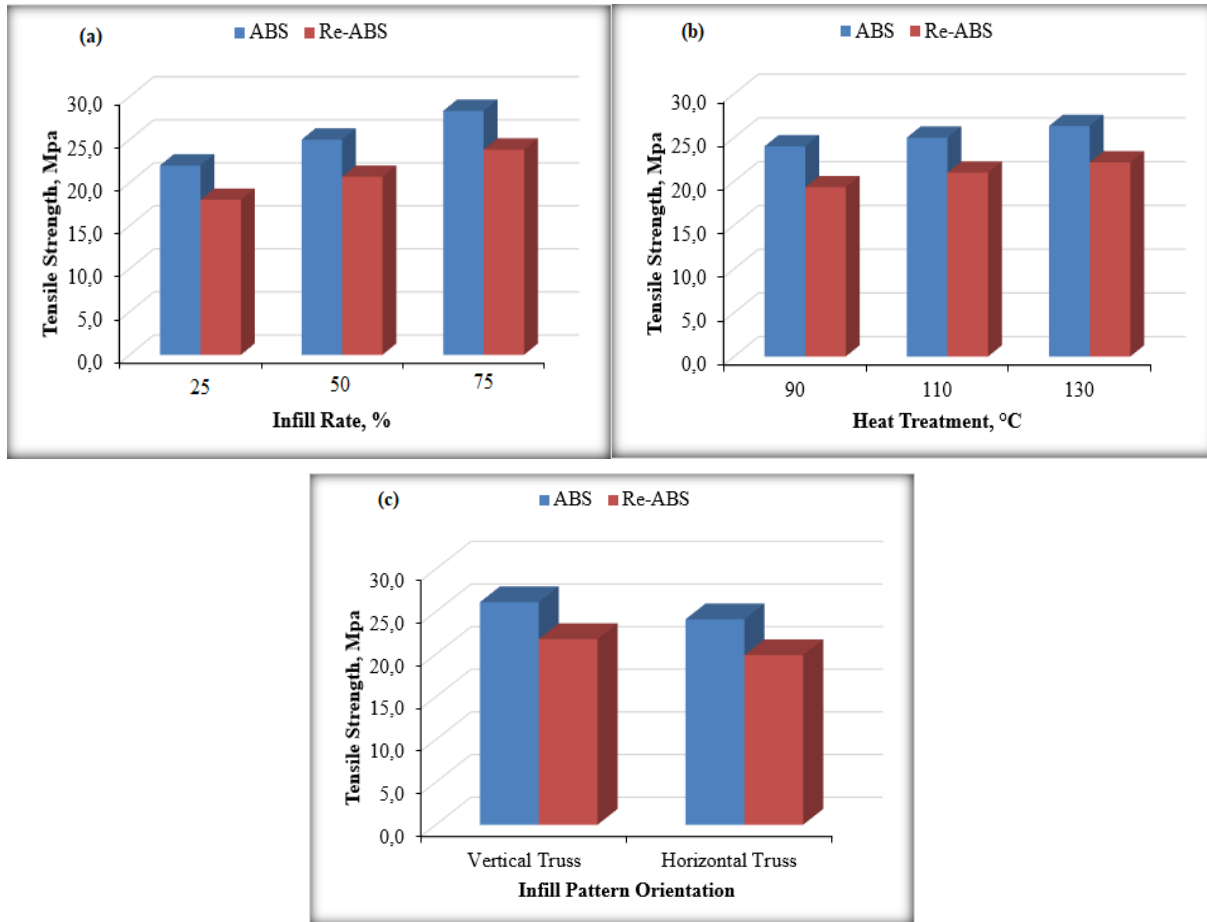


Figure 4. Tensile strength results of ABS and Re-ABS specimens depending on (a) infill rate, (b) heat treatment, and (c) infill pattern orientation parameters.

When examining the tensile strength graphs presented in Figures 4(a), (b), and (c), it was observed that tensile strength generally increased with increasing infill rate in both ABS and Re-ABS specimens. It was determined that increasing the infill rate from 25% to 50% increased the tensile strength by approximately 14% in ABS specimens and 15% in Re-ABS specimens; increasing it from 50% to 75% resulted in an increase of approximately 13–15% for both materials. It was seen that increasing the infill rate from 25% to 75% resulted in a total increase of 29% for ABS and 32% for Re-ABS. This increase is associated with a decrease in the void volume within the specimen and an increase in the effective cross-sectional area carrying the load as the infill rate increases. When evaluating the effect of heat treatment temperature, it was determined that an increase of approximately 4% in tensile strength occurred for ABS specimens and 9% for Re-ABS specimens when the temperature was increased from 90 °C to 110 °C. When the heat treatment temperature was increased from 110 °C to 130 °C, this increase was 5% for ABS specimens and 6% for Re-ABS specimens. When comparing the lowest (90 °C) and highest (130 °C) heat treatment temperatures, the total increase in tensile strength reached 10% for ABS and 15% for Re-ABS. This indicates that heat treatment is particularly effective in increasing chain flexibility and interlayer diffusion in Re-ABS material. It is thought that the heat treatment partially eliminates residual stresses formed during the FDM process, allows for the reorganisation of polymer chains, and strengthens interlayer bonding. The fact that this effect is more pronounced in Re-ABS material can be explained by the fact that the chain structures shortened by the recycling process can be more easily reorganised during heat treatment. When examining the effect of the infill pattern orientation, it was observed that specimens produced in the Vertical Truss direction exhibited higher tensile strength in both material groups compared to the Horizontal Truss direction. The average difference between the Vertical Truss and Horizontal Truss directions was determined to be around 8% for ABS and 9% for Re-ABS. This indicates that filament orientation parallel to the loading direction improves interlayer bonding, thereby increasing tensile strength.

Overall, it was determined that the most effective parameter on tensile strength was the infill rate. Increasing the infill rate improves load transfer by reducing the void ratio in the sample's internal structure and significantly increases mechanical strength. Heat treatment emerged as a secondary but important parameter, contributing to the improvement of mechanical performance, particularly in Re-ABS material.

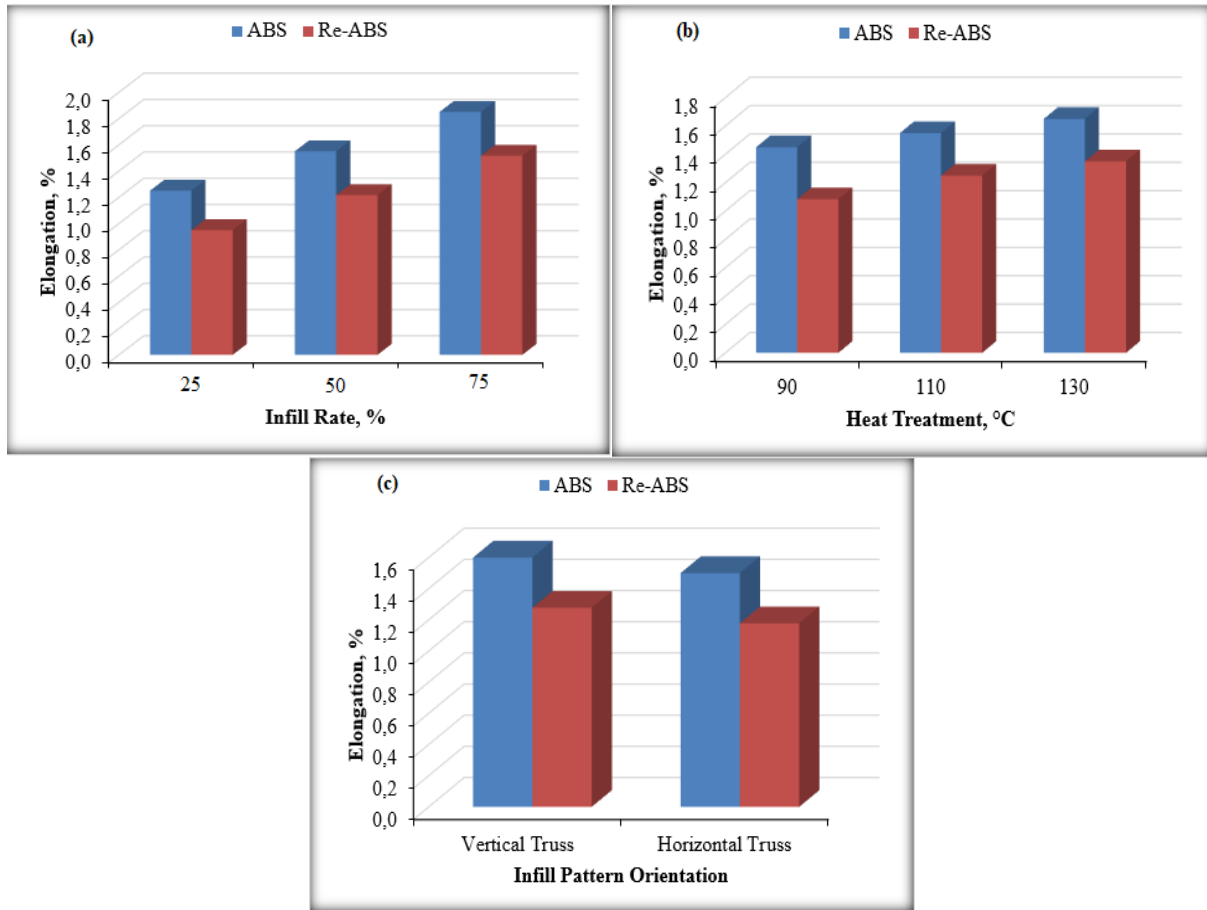


Figure 5. Results of elongation at break of ABS and Re-ABS specimens depending on (a) infill rate, (b) heat treatment, and (c) infill pattern orientation parameters.

When examining the graphs provided in Figures 5 (a), (b), and (c), it is observed that in ABS and Re-ABS specimens, the elongation at break generally increases as the fill rate and heat treatment temperature increase, while the effect of the infill pattern orientation remains more limited. When evaluating the impact of the infill rate, increasing the infill rate from 25% to 50% in ABS specimens resulted in an approximate 24% increase in elongation at break, while increasing it from 50% to 75% resulted in a 19% increase. The total increase from 25% to 75% reached 48%. In Re-ABS specimens, this increase was more pronounced, with increases of 28%, 25% and 60% observed in the same filling ranges, respectively. This is associated with a decrease in internal voids as the infill rate increases and the formation of a structure that allows for more homogeneous plastic deformation under load. The higher increase in Re-ABS specimens indicates that recycled material exhibits more sensitive behaviour to ductile deformation. When examining the effect of heat treatment temperature on elongation at break, an increase of approximately 7% in elongation at break was observed in ABS specimens when the temperature was increased from 90 °C to 110 °C, and an increase of 6% when the temperature was increased from 110 °C to 130 °C. Overall, an increase of approximately 14% was observed in the 90–130 °C range. In Re-ABS specimens, increases of 15%, 8% and 25% were observed in the same temperature ranges, respectively. The increase in heat treatment temperature improved the plastic deformation capacity by increasing the flexibility of the polymer chains. Furthermore, the strengthening of interlayer bonding delayed early fracture at the interfaces, increasing the elongation at break. The fact that this effect was more pronounced in the Re-ABS specimens can be explained by the recycled material exhibiting higher structural sensitivity to heat treatments.

When the effect of the infill pattern orientation was evaluated, the fracture elongation measured in the Vertical Truss structure of the ABS specimens was found to be approximately 6% higher than that in the Horizontal Truss structure. In Re-ABS specimens, this difference is approximately 8%. However, it is observed that the effect of the infill pattern orientation is more limited compared to the infill rate and heat treatment temperature, and remains a secondary parameter on elongation at break. Consequently, it was determined that the most influential parameter on elongation at break is the packing density. The packing density significantly increased the elongation at break in both ABS and Re-ABS materials by directly affecting the internal structure and deformation capacity of the sample. The heat treatment temperature emerged as a secondary parameter, while the effect of the infill pattern orientation remained more limited. Many studies in the literature are consistent with the results obtained in this study [18], [19].

3.2. Bending Test Results

Plastic, today's popular material, is used in many areas such as medical devices, beverage packaging, construction materials, and automotive components. In materials engineering, appropriate tests to characterise a material are very important before it is used in a specific product design. Among the many strength tests commonly used in the plastics industry, the bending or flexural test of a plastic strip can provide a great deal of information about the material's performance [20]. To present the three-point bending test results for ABS and Re-ABS specimens in a clearer and more comparable manner, the percentage change rates for increases and decreases in bending strength and bending modulus values were calculated, and these data are presented in graphs. Sub-sections (a), (b), and (c) of Figure 6 present graphical representations of the bending strength test results for ABS and Re-ABS specimens, respectively, based on the infill rate, heat treatment, and infill pattern orientation. In contrast, Figure 7 (a), (b), and (c) show the graphical distributions of the bending modulus test results for ABS and Re-ABS specimens according to the same parameters.

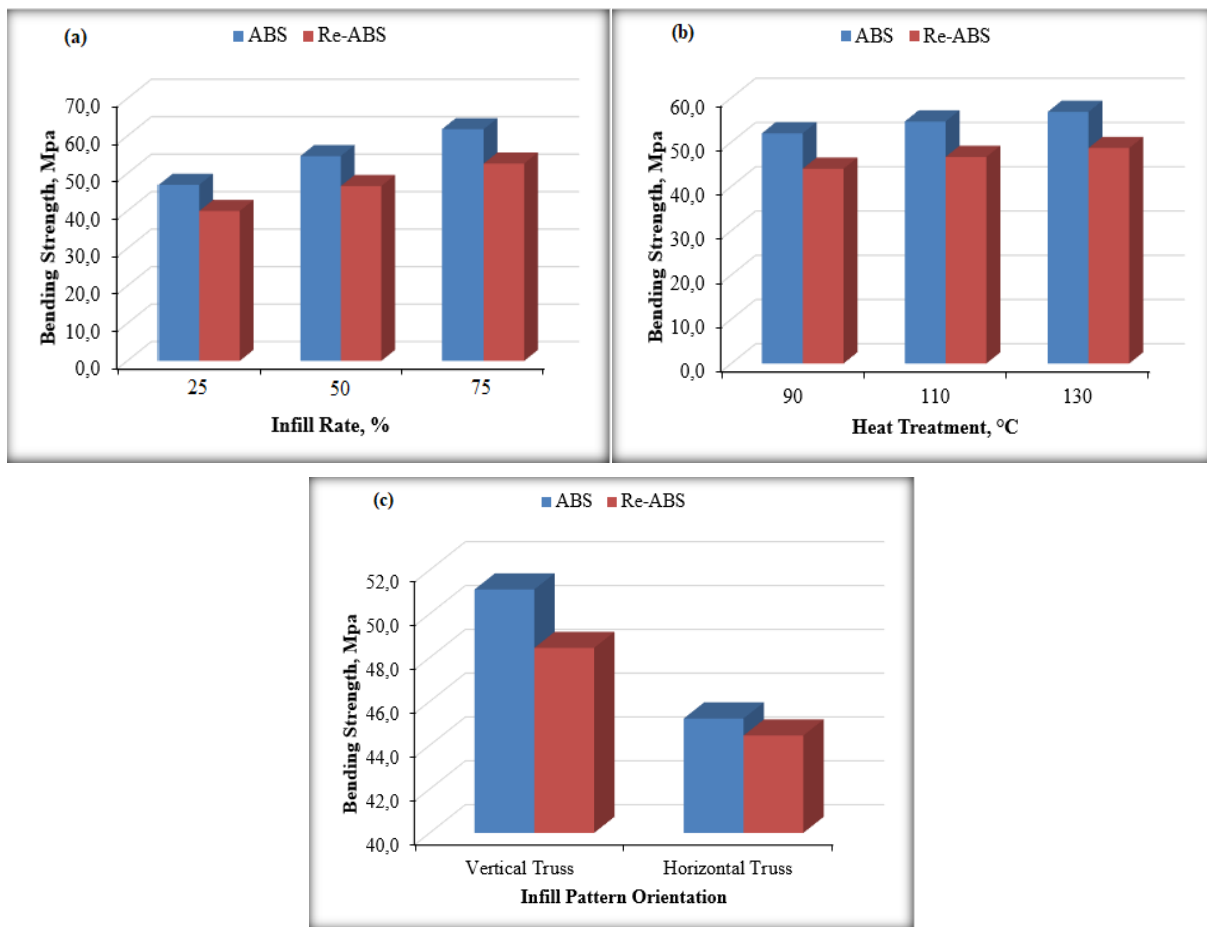


Figure 6. Bending strength results of ABS and Re-ABS specimens depending on (a) infill rate, (b) heat treatment, and (c) infill pattern orientation parameters.

When examining the bending strength graphs presented in Figures 6(a), (b), and (c), it was observed that the bending strength generally increased with increasing fill rate in both ABS and Re-ABS specimens. It was determined that increasing the infill rate from 25% to 50% resulted in an approximate 16% increase in the bending ratio for ABS specimens and a 17% increase for Re-ABS specimens; increasing it from 50% to 75% resulted in an additional approximate 13% increase for both materials. It was seen that increasing the infill rate from 25% to 75% resulted in a total increase of 32% in both ABS and Re-ABS specimens. These results are associated with a decrease in the void ratio in the internal structure of the specimens as the infill rate increases and a more homogeneous deformation behaviour under bending load. When evaluating the effect of heat treatment temperature on the bending ratio, it was determined that the bending ratio increased by approximately 5% in ABS specimens and 6% in Re-ABS specimens when the temperature increased from 90 °C to 110 °C. When the heat treatment temperature increased from 110 °C to 130 °C, this increase was approximately 4% for both material groups. When comparing the lowest (90 °C) and highest (130 °C) heat treatment temperatures, the total increase in the bending ratio was found to be 9% for ABS and 11% for Re-ABS. The effect of heat treatment in increasing the bending modulus can be explained by the polymer chains gaining greater flexibility with increasing temperature, improved interlayer bonding, and the formation of a microstructure that allows for greater plastic deformation under bending load. The higher increase in Re-ABS specimens indicates that recycled material is more sensitive to structural rearrangements after heat treatment. When examining the effect of the infill pattern orientation, it was determined that the bending ratio values of the specimens produced in the Vertical Truss direction were higher compared to the Horizontal Truss direction. It was determined that the values obtained in the Horizontal Truss direction were approximately 12% lower in ABS specimens and 8% lower in Re-ABS specimens compared to the Vertical Truss direction. This situation is associated with the filaments in the Vertical Truss structure participating more effectively in deformation under bending load. As a result of the overall evaluation, it was determined that the most effective parameter on the bending ratio was the infill rate. The infill rate plays a more dominant role than the heat treatment temperature and infill pattern orientation, directly affecting the amount of voids in the internal structure of the specimen and its deformation capacity.

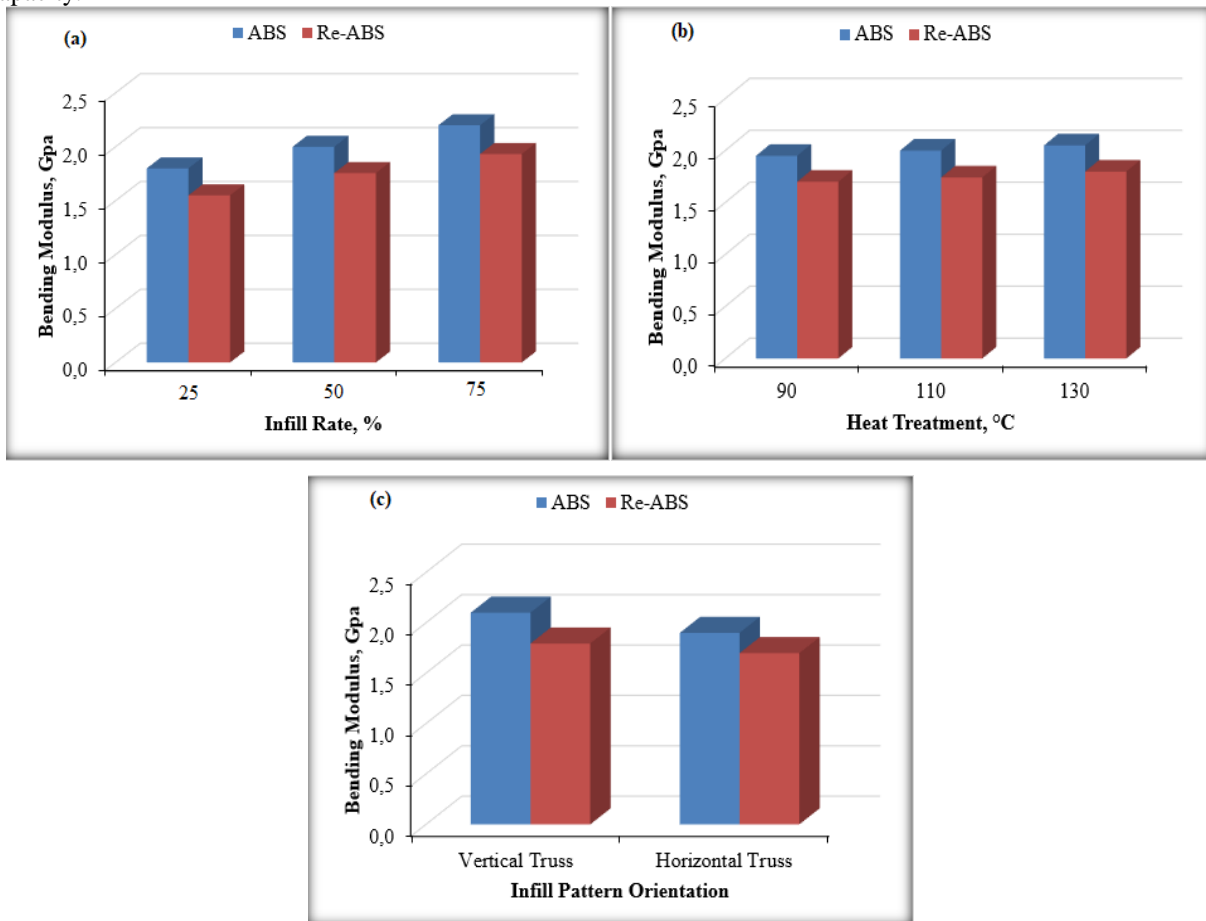
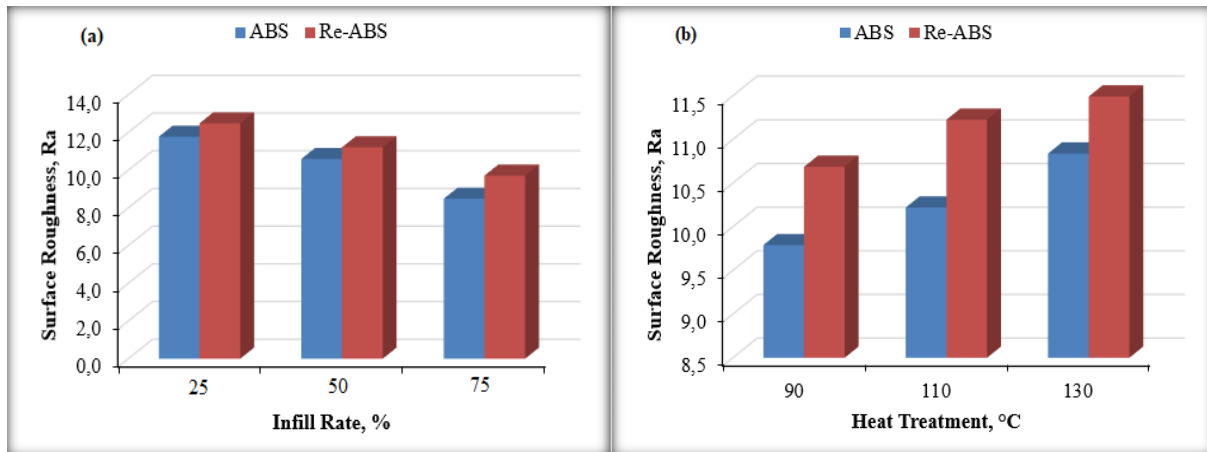


Figure 7. Bending modulus results of ABS and Re-ABS specimens depending on (a) infill rate, (b) heat treatment, and (c) infill pattern orientation parameters.

When examining the bending modulus graphs given in Figures 7(a), (b), and (c), it is observed that the bending modulus increases significantly with increasing infill rate in both ABS and Re-ABS specimens. Increasing the infill rate from 25% to 50% resulted in an approximate 11% increase in the bending modulus for ABS specimens and a 13% increase for Re-ABS specimens. Increasing it from 50% to 75% resulted in an additional approximate 10% increase for both materials. With the infill rate increased from 25% to 75%, the total increase reached 22% for ABS and 25% for Re-ABS. These results demonstrate that as the infill rate increases, the rigidity of the specimens increases, and they exhibit higher elastic resistance under bending load. When evaluating the effect of heat treatment temperature on the bending modulus, it was determined that the bending modulus increased by approximately 3% in ABS specimens and 2% in Re-ABS specimens when the temperature increased from 90 °C to 110 °C. When the heat treatment temperature increased from 110 °C to 130 °C, this increase was calculated to be 2% for ABS and 3% for Re-ABS. When the lowest and highest heat treatment temperatures were compared, the total increase in the bending modulus remained at 5% for ABS and 6% for Re-ABS. This limited increase in the bending modulus stems from the fact that heat treatment does not have as pronounced an effect on the material's elastic rigidity as it does on strength and elongation. Heat treatment primarily affects chain flexibility and plastic deformation behaviour, playing a secondary role in the elastic modulus. When evaluated in terms of infill pattern orientation, it was observed that specimens produced in the Vertical Truss direction had higher bending modulus values in both material groups compared to the Horizontal Truss direction. The average difference between the Vertical Truss and Horizontal Truss directions was determined to be approximately 10% for ABS and 5% for Re-ABS. This result indicates that the placement of filaments more parallel to the loading direction increases the bending rigidity of the sample. Overall, it was concluded that the most influential parameter on the bending modulus was the infill rate. An increase in the infill rate had a more pronounced effect on the bending modulus than the heat treatment temperature and infill pattern orientation, by increasing the effective cross-sectional area and internal structural integrity of the sample [21].

3.3. Surface Roughness Results

Surface roughness values have a direct impact on abrasion resistance, friction coefficient, coating and adhesion performance, biocompatibility, and aesthetic surface quality of polymers. Especially in polymers produced by 3D printing, surface morphology is highly sensitive to production parameters due to the layered production structure. Changes in parameters such as infill rate, heat treatment, and infill pattern orientation can lead to significant differences in surface roughness. Therefore, roughness measurements provide important information for optimising the production process and ensuring the desired surface quality. Figure 8 (a), (b), and (c) show the graphs of surface roughness (Ra) measurement results of ABS and Re-ABS specimens depending on the infill rate, heat treatment, and infill pattern orientation, respectively.



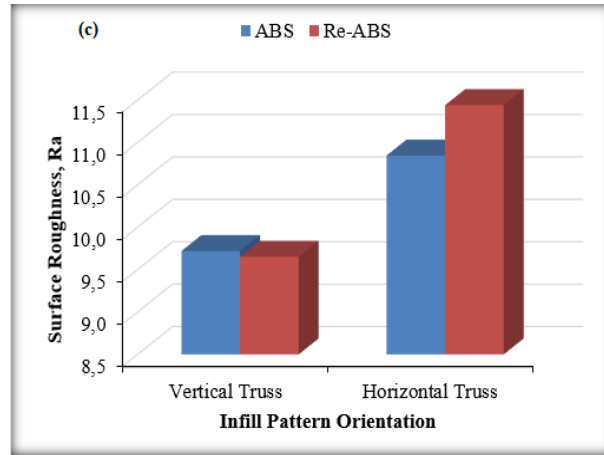


Figure 8. Surface roughness (Ra) results of ABS and Re-ABS specimens depending on (a) infill rate, (b) heat treatment, and (c) infill pattern orientation parameters.

When the surface roughness results presented in Figure 8 (a), (b), and (c) are evaluated, a general decreasing trend is observed in the surface roughness values of ABS and Re-ABS specimens with the increase in the infill rate. When the infill rate was increased from 25% to 50%, the surface roughness decreased by approximately 10% for ABS specimens and by approximately 10% for Re-ABS specimens. When the infill rate was increased from 50% to 75%, this decrease was 20% for ABS and 13% for Re-ABS. When the lowest and highest infill rates were compared, it was determined that the total roughness reduction reached 28% in ABS and 22% in Re-ABS. This is attributed to the fact that the increased infill rate reduces the interlayer voids and creates a more continuous and smooth surface morphology. When the effect of heat treatment temperature on surface roughness was analysed, it was determined that the surface roughness increased by approximately 4% for ABS specimens and 5% for Re-ABS specimens when the heat treatment temperature was increased from 90 °C to 110 °C. When the heat treatment temperature was increased from 110 °C to 130 °C, this increase was 6% for ABS and 2% for Re-ABS. When the lowest (90 °C) and highest (130 °C) heat treatment temperatures were compared, the total increase in surface roughness was calculated as 11% for ABS and 8% for Re-ABS. This limited increase in roughness after heat treatment can be explained by the fact that polymer chains tend to reflow towards the surface at high temperatures, and layer boundaries become more pronounced. However, the fact that the increased rates remained at low levels indicates that the applied heat treatment temperatures were kept below the critical thresholds that would adversely affect the surface quality. When evaluated in terms of infill pattern orientation, it was found that the specimens produced in the Horizontal Truss direction exhibited higher surface roughness in both material groups compared to those produced in the Vertical Truss direction. The average difference between Vertical Truss and Horizontal Truss directions was found to be 12% for ABS and 19% for Re-ABS. This may be attributed to the fact that the layer stepping effect is more pronounced on the surface in the Horizontal Truss direction. In general, it is concluded that the most effective parameter on surface roughness is the fill rate. The infill rate plays a more dominant role in surface quality compared to heat treatment temperature and infill pattern orientation, as it directly affects the integrity of the sample microstructure and layer transitions [22], [23].

3.4. Hardness Test Results

Hardness testing of polymer materials is a fundamental characterisation method in terms of both understanding the mechanical behaviour accurately and evaluating the suitability of the material for the application. In order to present the hardness measurement results of ABS and Re-ABS specimens more clearly and comparably after the test, the percentage change rates of the increases and decreases in hardness values were calculated, and these data were shown in graphs. Figure 9 (a), (b), and (c) show the graphs of hardness test results of ABS and Re-ABS specimens depending on the infill rate, heat treatment, and infill pattern orientation, respectively.

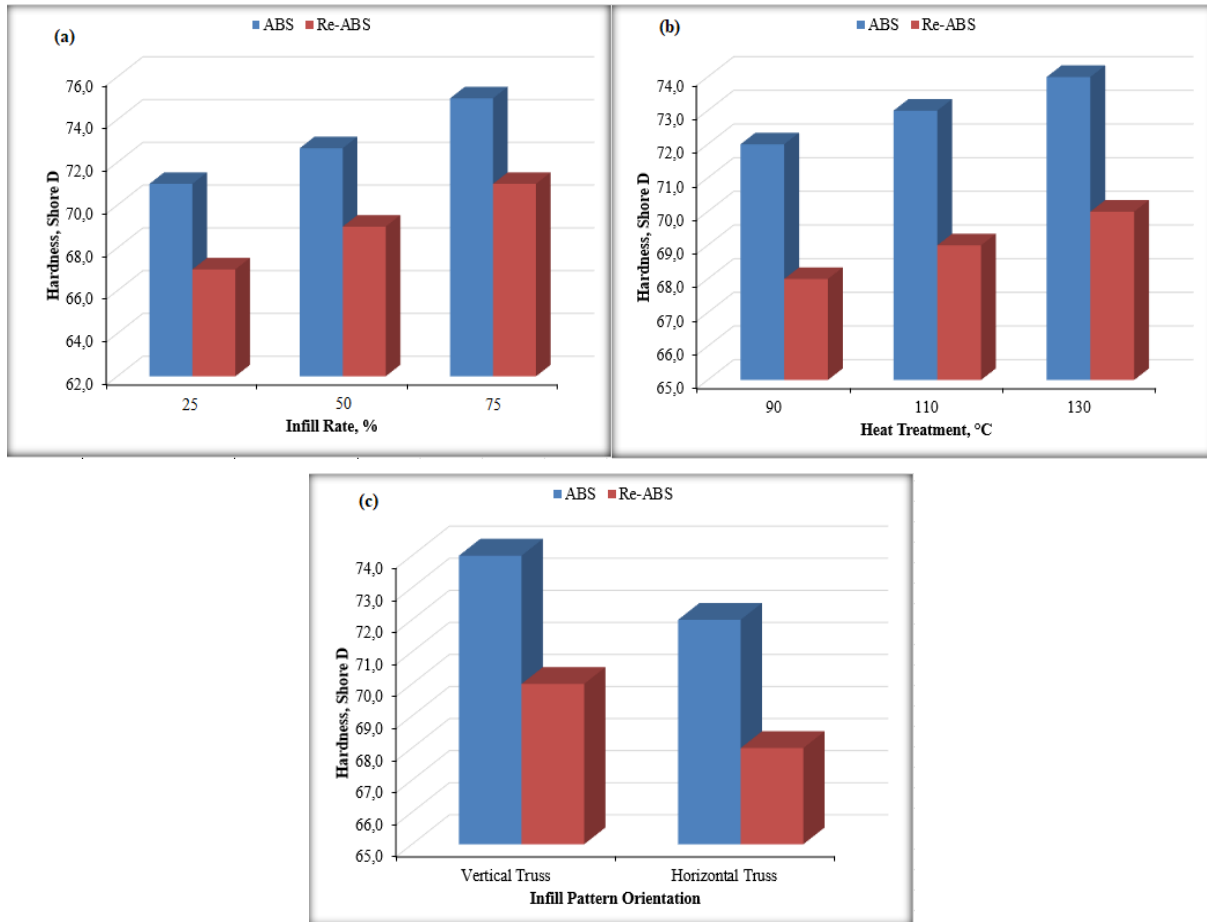


Figure 9. Hardness results of ABS and Re-ABS specimens depending on (a) infill rate, (b) heat treatment, and (c) infill pattern orientation parameters.

When the Shore D hardness values given in Figure 9 (a), (b), and (c) are analyzed, it is seen that the increase in the infill rate has a positive effect on the hardness of ABS and Re-ABS specimens. When the infill rate increased from 25% to 50%, the hardness values increased by approximately 2% for ABS specimens and 3% for Re-ABS specimens. When the infill rate increased from 50% to 75%, an additional hardness increase of approximately 3% occurred for both materials. It was determined that the total hardness increase reached 7% in ABS and 6% in Re-ABS by increasing the infill rate from 25% to 75%. These results can be explained by the fact that the internal structure of the sample becomes more compact and the resistance of the surface to penetration increases with increasing infill rate. When the effect of heat treatment temperature on hardness was evaluated, it was determined that the hardness increase in both material groups was approximately 1% in the transition from 90 °C to 110 °C. Similarly, a limited increase in hardness from 110 °C to 130 °C was again realised around 1%. When the lowest and highest heat treatment temperatures were compared, the total hardness increase was approximately 3% for both ABS and Re-ABS specimens. When the effect of the infill pattern orientation was analyzed, it was determined that the specimens produced in the Vertical Truss direction had approximately 3% higher hardness values in both material groups compared to the Horizontal Truss direction. This situation is associated with the more dense and continuous placement of filaments on the surface in the Vertical Truss structure. In general, it is concluded that the most effective parameter on hardness is the infill rate. The infill rate directly affects the density and surface integrity of the sample microstructure and has a more pronounced effect on hardness compared to heat treatment temperature and infill pattern orientation [24].

3.5. SEM Analysis

SEM analyses play an important role in determining the fracture mechanism and damage causes in polymer materials. By examining the fracture surface morphology, ductile or brittle fracture behaviour, interlayer bonding,

and the presence of micro defects can be revealed. Figure 10 (a) and (b) show the SEM images taken at different magnifications of ABS specimens produced in Vertical Truss and Horizontal Truss directions, respectively, and Figure 11 (a) and (b) show the SEM images taken at different magnifications of Re-ABS specimens produced in the same production directions.

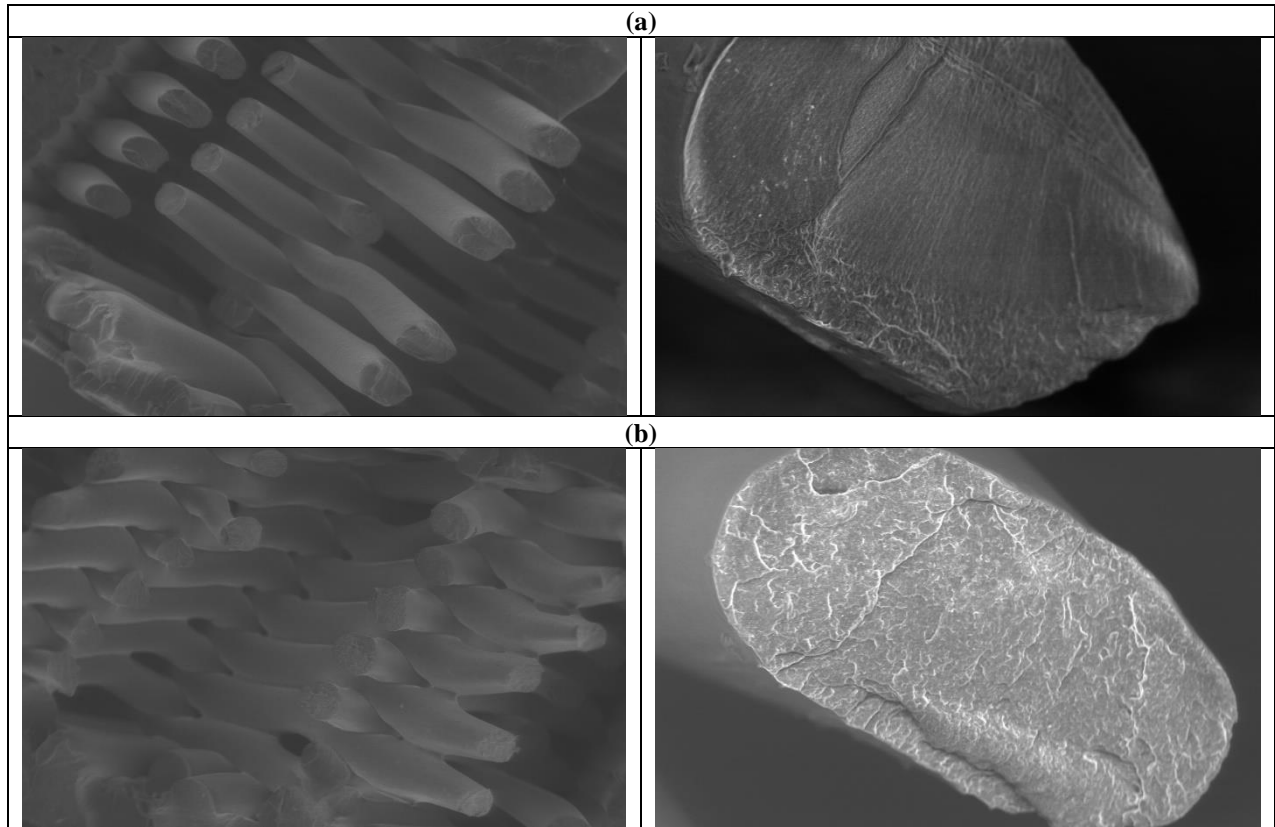
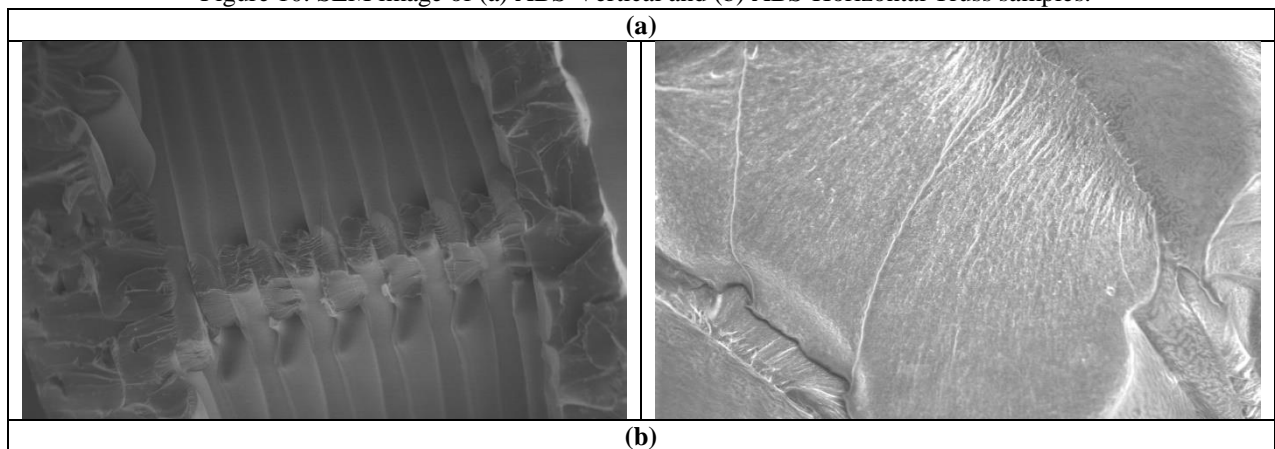


Figure 10. SEM image of (a) ABS-Vertical and (b) ABS-Horizontal Truss samples.



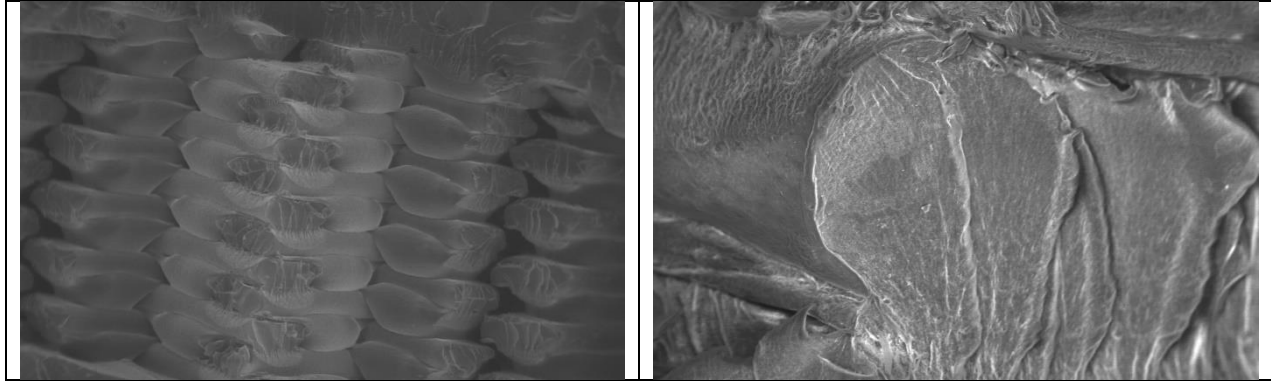


Figure 11. SEM image of (a) Re-ABS-Vertical and (b) Re-ABS-Horizontal Truss samples.

When the SEM images of ABS-Vertical and ABS-Horizontal Truss specimens given in Figure 10 (a) and (b) are analyzed, it is seen that the fracture surface morphology shows significant differences depending on the production direction. In ABS-Vertical Truss specimens, it was found that the filaments were placed more parallel to the loading direction, the interlayer bonding was continuous, and the interfacial boundaries were largely indistinct. The rough and fibrous structure observed on the fracture surface indicates that plastic deformations occurred during fracture. In addition, deformation lines and local necking marks indicate that ductile fracture behaviour is dominant in ABS specimens. In heat-treated ABS specimens, it is evaluated that the interlayer diffusion improves and the interfacial continuity increases as a result of the reorganisation of the polymer chains under the effect of increasing temperature. This is supported by the fact that filament boundaries become less prominent and fibrous fracture morphology becomes dominant in SEM images. In the SEM images of the ABS-Horizontal Truss specimens, it was observed that the interlayer boundaries were more prominent and the fracture progressed mainly along the filament interfaces. A limited number of microvoids and interfacial separations were detected in these regions, indicating that filament placement perpendicular to the loading direction adversely affects the interlayer bond strength. Although heat treatment was applied, the fact that the filament alignment in the Horizontal Truss direction was unfavourable to the loading direction prevented the complete elimination of interfacial weaknesses. It has been similarly reported in the literature that interlayer adherence in ABS materials, depending on the manufacturing direction, is determinant on mechanical behaviour [25]-[27]. When the SEM images of Re-ABS-Vertical and Re-ABS-Horizontal Truss specimens presented in Figure 11 (a) and (b) are analyzed, it is seen that the recycling process has significant effects on the fracture surface morphology. It was found that the inter-filament bonding was more irregular in Re-ABS-Vertical Truss specimens compared to ABS specimens, and microcracks and voids were formed in some areas. The rougher and heterogeneous structure observed on the fractured surface is considered as an indicator of the breaks in the polymer chains as a result of thermomechanical effects occurring during recycling. In heat-treated Re-ABS specimens, despite the increase in chain mobility, it is observed that the interlayer bonding cannot gain a homogeneous structure as much as ABS due to the decrease in molecular weight. This is clearly demonstrated by the presence of irregular interfaces and local voids in SEM images. In the Re-ABS-Horizontal Truss specimens, it was observed that interlayer separations became more pronounced, and fracture occurred mostly along the weakened interfaces. Irregular fracture marks and large microvoids observed at the filament ends indicate that loss of ductility has occurred in the recycled ABS material due to molecular weight reduction. It is understood that heat treatment partially improved the interfacial bonding in these specimens, but could not completely compensate for the structural disadvantages due to the production direction. Similarly, chain degradation, viscosity reduction, and mechanical strength decrease after recycling in Re-ABS materials have been reported in the literature [28]-[30].

4. CONCLUSION

The general results obtained within the scope of this study are presented below in bullet points:

- It has been determined that the most effective parameter on tensile strength and elongation at break is the infill rate. Increasing the infill rate has improved load transfer. Heat treatment temperature has increased mechanical performance, particularly in Re-ABS specimens, while the effect of the infill pattern orientation has remained limited.

- Bending strength and bending modules have increased with the rise in infill rate. Heat treatment has positively affected bending behaviour, with specimens produced in the Vertical Truss direction exhibiting higher bending performance.
- Surface roughness decreased with increasing infill rate and increased to a limited extent with increasing heat treatment temperature. Higher roughness values were obtained in the Horizontal Truss direction.
- It has been observed that the degree of infilling is a determining factor in hardness. The effects of heat treatment and infill pattern orientations on hardness have been limited, with Re-ABS specimens exhibiting hardness values close to those of ABS.
- SEM analyses have demonstrated that the infill pattern orientation and recycling process significantly influence fracture morphology. Stronger interlayer bonding was observed in the Vertical Truss direction, while more heterogeneous fracture surfaces were noted in the Re-ABS specimens.

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