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Comparison of The Mechanical Properties of Three-Dimensionally Printed Orthodontic Models with Different Materials and Infill Parameters

DOCTOR OF PHILOSOPHY THESIS

YAVUZ DENİZ TANKUTER, DDS

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APPROVAL

This thesis has been deemed by the jury in accordance with the relevant articles of Yeditepe University Graduate Education and Examinations Regulation and has been approved by Administrative Board of Institute with decision dated ………… and numbered ………...

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DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree except where due acknowledgment has been made in the text.

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Yavuz Deniz Tankuter

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3DPIHA	**3d Printing In-House Aligner Technology**
CAD-CAM	**Computer-Aided Design/Computer-Aided Manufacturing**
CT	**Computed Tomography**
PET	**Polyethylene Terephthalate**
PET-G	**Polyethylene Terephthalate Glycol**
TPU	**Thermoplastic Polyurethane**
SLA	**Stereolithography**
FDM	**Fused Deposition Modeling**
PBF	**Powder Bed Fusion**
SLM	**Selective Laser Melting**
SLS	**Selective Laser Sintering**
EBM	**Electron Beam Melting**
DMLS	**Direct Metal Laser Sintering**
DLP	**Digital Light Processing**
PJ	**Photo Jet**
PLA	**Polylactic Acid**
PLA-GO	**Polylactic Acid - Graphene Oxide**
MPa	**Mega Pascal**

ABSTRACT

Tankuter, Y.D. (2023). Comparison of the Mechanical Properties of Three-Dimensionally Printed Orthodontic Models with Different Materials and Infill Parameters. Yeditepe University, Institute of Health Sciences, Department of Orthodontics PhD Thesis, İstanbul.

In this study, our purpose was to collect data by comparing the effect of the compressive strength on two different polymers, in order to reduce the time and the cost of 3D orthodontic model printing. Our specimens are produced from 'Esun ABS+' brand filament (Acrylonitil, 1-3, butadiene styrene) printed in 'Creality Ender-3 S1 Pro' brand FDM printer and 'Anycubic standard 3d printing resin (1-methyl-1,2ethanediyl) bis[oxy(methyl-2,1-ethanediyl)] diacrylate printed in 'Anycubic Mono X' brand DLP type printer. In our research, two different printing materials ABS and Resin are the two main groups. The subgroups of these two main groups were designed in 'UltiMaker Cura' software as rectangular prisms which are designed as 30%, 60%, 80 % and 100% infill patterns. Printing was carried out with ten samples for each subgroup. With the power analysis, ‘G*power 3.1’each group's sample size was planned to be 10. The plastic deformation values of the samples were recorded on the Instron Universal Testing machine. All groups were compared with each other, and the results were statistically analyzed. Between the maximum load averages in the compressive strength of the groups with the 80 % and 100% infill ratio no statistically significant difference was observed. ($p=0.097$ for ABS, $p=0.092$). Except this one, between all the other groups statistically significant differences have been observed ($p<0.05$). As compressive force applied when printing clear aligners is about 0.4 MPa, all groups have enough compressive strength for the 3D orthodontic model production. When 30% infill subgroup was compared with all the other subgroups, statistically significant difference was observed ($p<0.05$). Similar studies should be conducted in groups with an infill rate below 30% in future research.

Keywords: Resin, ABS, FDM, DLP, 3D dental model, aligner, compressive strength

ÖZET

Tankuter, Y. D. (2023) Üç Boyutlu Yazıcı Tarafından Farklı İç Yapılara Sahip ve Farklı Malzemeler Kullanılarak Üretilmiş Ortodontik Modellerin Mekanik Özellikleri. Yeditepe Üniversitesi, Sağlık Bilimleri Enstitüsü, Ortodonti Anabilim Dalı. Doktora Tezi İstanbul.

Bu çalışmada amacımız iki farklı polimerin üzerine uygulanan baskı direncine gösterdikleri reaksiyonları karşılaştırarak en az materyalle en hızlı model üretimi sağlanması amacıyla veri toplamaktır. Materyalimizi oluşturan örnekler, 'Creality Ender-3 S1 Pro' marka FDM printerda basılmış, 'Esun abs+' marka filament (Akrilonitil,1-3, butadien sitirien) ve 'Anycubic Mono X' marka DLP tipi printerda basılmış 'Anycubic Standard 3D Printing Resin'den ((1-methyl-1,2ethanediyl) bis[oxy(methyl-2,1-ethanediyl)] diacrylate) üretilmiştir. Bu çalışmada, yapı malzemelerine göre, resin ve ABS olmak üzere iki ana grup oluşturuldu. Bu iki ana grubun alt grupları, %30, %60, %80 ve %100 doluluk oranlarına sahip dikdörten prizması olacak şekilde 'UltiMaker Cura' programında tasarlandı. Çalışmamız ile ilgili G*power 3.1 programı ile yapılan güç analizinde her çalışma grubunun örneklem genişliği 10 olarak bulundu. Her alt gruptan 10'ar örnek olacak şekilde baskı işlemi gerçekleştirildi. Örneklerin Instron Universal Testing cihazında, plastik deformasyona uğradığı değerler tespit edildi. Sonuçlar değerlendirildiğinde her iki grupta da % 80 ve % 100 doluluk oranına sahip grupların basma gerilmesinde maksimum yük ortalamaları arasında istatistiksel olarak anlamlı farklılık gözlenmemiştir. (ABS için $p=0,097$, Resin için $p=0,0921$). Bu iki grup arasındaki karşılaştırma dışındaki tüm gruplar arası karşılaştırmalarda istatistiksel olarak anlamlı farklılık bulunmuştur. ($p<0.05$). Şeffaf plakların basılması esnasında uygulanan baskı kuvvetinin yaklaşık 0.4 MPa civarında olduğu göz önüne alındığında tüm gruplar şeffaf plak basımı için gerekli baskı dayanımını göstermektedir. %30 doluluk gösteren grup ile diğer tüm gruplar arasında yapılan bütün karşılaştırmalarda anlamlı fark bulunmuştur ($p<0.05$). %30 doluluk oranı altında doluluk gösteren gruplarda benzer çalışmalar yapılması yararlı olacaktır.

Anahtar Kelimeler: Resin, ABS, FDM, DLP, dental model, aligner, basma gerilme direnci

1. INTRODUCTION AND PURPOSE

The purpose of orthodontics is to provide an aesthetic and healthy functioning oral and maxillofacial system. Considering these purposes, correct diagnosis and treatment planning should be made, and the planned treatment should be applied without compromising the principle of not harming the patient.

Nowadays, the doctors and the patients' expectations are aesthetic and economic treatments and short treatment periods (1). The improvements in the clear aligner therapy are the driving force for the use of computer technology in orthodontics. Although aligner therapy decreases the chair time, the time spent on computers and 3D printers is increased. (2)

The costs of software, printers, 3D model materials and aligner materials decrease as competition among companies increase. One of the aims of scientific studies is to reduce these costs to an optimum level.

Today, clear aligners have evolved to a level where all dental and skeletal orthodontic treatments can be achieved. The final point reached in this evolution process is the '3D printing in-house aligner technology', which moves the production of the aligners from companies to clinics.

The purpose of the scientific studies of orthodontics can be summarized as shortening the time, reducing the cost of the treatment, and increasing the aesthetic and comfort level of the patient. Scientific studies are carried out to improve the structural properties of materials used to reduce labor and cost of the 3D model production (3)(4).

In today's world, where petrol and petroleum products are an integral part of our lives, environmental awareness has been one of the reasons that prompted us to undertake this study. Almost all materials, such as filaments and resins, used in aligner treatment are petroleum-based. When we consider the three-dimensional models and numerous clear aligners used in orthodontic treatments, it can be perceived as a threat to the environment. In our study, we aimed to reduce the amount of model material as much as possible in order to minimize the environmental pollution caused by treatment residues (5).

The purpose of this study is to compare the reaction of two different model materials with different infill ratios under the compressive strength imitating the thermoforming machine.

2. LITERATURE REVIEW

2.1. History

In 1925, Orin Remensnyder noticed that the gingival massage appliance,"Flex-o-Tite", caused some unwanted tooth movements. (6)

In 1945, Harold D. Kesling invented the retention appliance that he called ‘The Positioner’. He pioneered the possibility of tooth movement with thermoplastic materials (7). Kesling proposed the first idea for aligner treatment, predicting that major tooth movements could be made with a series of positioners.

In 1964, Henry Nahoum improved Kesling's technique and made some dental changes on the patients’ models. He started clear aligner therapy with the appliances he made by transparent materials such as acetate, vinyl, styrene, and polyethylene with vacuum device (8).

In 1971, Ponitz started to use biocryl (polymethyl methacrylate) in the production of an "invisible retainer". He used thermoforming process for the production of the appliances that he used for finishing and retention. He planned a few minor tooth movements on the model during the finishing phase (9).

In 1985, Mc Namara used finishing and retainer appliances by using 1mm Biocryl polymer that Ponitz used earlier in his technique. He used Biostar during aligner production. The difference between previous appliances and vacuum instruments is that Biostar uses positive air pressure. Mc Namara agrees that both appliances are not as durable as the conventional acrylic retainers in long-term usage (9,10).

In 1993, Jack Sheridan developed clear aligners and introduced the ‘essix’ appliance into the world of orthodontics by using thermoplastic co-polyester 0.030’ polypropylene, a Raintree product and he developed an aesthetic treatment method for aligning teeth. He also started the use of IPR in incisors. Like Mc Namara, he manages to minimize the thickness of the plates by using positive air pressure (11). Until this stage, clear aligner treatments could be used to correct minimal crowding and the production process was very time-consuming and labor-intensive.

Zia Chisthy, a student at Stanford University in 1997, developed a computer-aided system with his orthodontist friends while undergoing orthodontic treatment and created the software of the first aligner technology. In 1998, Zia Chishty and Kelsey Wirth first introduced a treatment called Invisalign (Align Technology, Ca, USA) using a series of removable polyurethane aligners. This thermoplastic and transparent polymeric material has created the beginning of new horizons together with CAD/CAM technology (12). Treatment with clear aligners consists of a multi-step system. Individual crown segmentation is performed with a computer algorithm, and the treatment plan is determined via the preferred software. 3D dental models suitable for the treatment stages are printed; and after post-processing, aligners are prepared by thermoforming on these models (13).

Nowadays aligner technologies are evolving to treat all dental and skeletal orthodontic malocclusions. In clear aligner therapy, the technique has evolved over the years to be aesthetically pleasing, comfortable and effective.

2.2. Aligners

With the use of the intraoral scanner, clinical problems arising from traditional impression-taking procedures have been eliminated, and the obtained digital records can be stored in the digital environment with all their details intact. Targeted orthodontic movements are arranged on CAD platforms. CT (computerized tomography) is used if any information about root or bone is necessary.

The first step of aligner treatment begins with obtaining digital records from the patient's mouth or dental models. The records are transferred to a digital platform where they are applied to the CAD-CAM technology (14). On the preferred software, the positions of the teeth are planned by arranging sequential virtual models. At this stage, 3D models on which aligners will be made are printed individually. Technology is used most intensively in the aligner manufacturing process during the production of 3D models. The process of 3D model production is challenging in terms of time, labor and cost, it requires new studies to be conducted. The goal of the advancing technology is leaning towards the process of printing aligners directly by 3D printers according to digital design (25). Thus, the environmental pollution of plastic waste caused by 3D models will be eliminated (4).

The direct printing of the aligners reduces the environmental pollution problems due to 3d printed dental models. Direct printed aligners are more accurate, less time consuming than the conventional ones. Thermoplastic polymers and polymer blends are the most common chemicals used in producing aligners (16).

Although Invisalign (Align Technology, Ca, USA) was the first brand to be used in this market, many new brands such as 3M™ Clarity™ Aligners, Clear Correct™, Spark™ Clear Aligner System, SureSmile®, Reveal® Clear Aligners (Henry Schein®), Maraligner (Turkey) were also introduced.

Today, many new brands are entering the market, and this large-scale and successful competitive environment positively affects the development of aligner technology. High expectations create opportunities for new research in orthodontics.

Studies continue in the world of orthodontics, in order for aligners to achieve perfection. The features such as high resilience, low stiffness, sufficient elasticity, adequate resistance to varied strength and distortion, excellent transparency, low cytotoxicity, and high biocompatibility are the perfection expectations of aligner therapy (17).

During the production of aligner, the material is heated until around $110C^0$ with a heat-forming process called thermoforming. Thermoforming process adapts the aligner material to the 3D printed dental model. At the end of the thermoforming process, it was determined that the transparency, thickness, and stiffness of all aligner materials change. (18-19)

It has been determined that the polyurethane material used in the production of aligners have produced better adaptation than all other materials (20-21).

Science is trying to produce smart materials that can provide predictable and repetitive responses to different external stimuli, such as electricity, heat, and magnetism; and today successful breakthroughs are being made in this regard (stimuli-response materials) (22).

The "Shape Memory" material, which has just started to be used in orthodontics, can change its shape, and return to its original shape after each use (23-24). When reached to the transition temperature around $67C^0$, the shape memory polymer, shows elastic properties; when it is applied to the patient's mouth it returns to its previous shape and it applies the necessary force to the teeth (25).

South Korean manufacturer Graphy (Seoul, Korea) has introduced the first 3D printed aligner and claimed that with this polymer less frequent aligner change is needed, so overall used aligner number will be reduced.

Trending aligner technology is developing rapidly in the direction of "3D Printing In-House Aligners". Scientific studies continue for the production of more sensitive and environmentally friendly 3D models which will reduce labor, time and costs, with the prediction that the need for 3D models in orthodontics will continue for a long time.

In aligner technology, where petroleum-based materials such as PET, PETG or TPU are used, it is necessary to target the recyclability of the materials used. The intent should be to use biodegradable materials (26).

Considering that patients wear clear aligners for 20 hours a day and that these aligners are produced from petroleum-based plastic materials, they may have adverse effects on general health. Comparative studies are being conducted on the cytotoxic effects. Ahamed SF et al, determined that the toxicity of 3D printed materials decreases gradually during the post-polymerization process (27).

2.3. The Use of Three-Dimensional Printers in Dentistry:

3D printers are used in dentistry for the following purposes:

- Orthodontic clear aligner treatments
- Mandibular and facial reconstruction (preoperative surgical planning)
- Dental Education
- Prosthodontics
- Crown and bridge dentures
- Complete dentures
- Removable partial dentures
- Applications in oral and maxillofacial surgery
- Occlusal splint construction
- Surgical implants
- Oral implantology: surgical guides, three-dimensional printed custom trays

Waldecker et al, point out that in prosthodontics, aesthetic dentistry and orthodontics, the internal structures and surface accuracy of 3D models are as important as their dimensional compatibility and stability. (28)

2.4. The Types of Printers Used in Dentistry

In 1986, Charles Hull discovered 3D printing technology (34-35). He patented Stereolithography (SLA) and put this method on the market.

In 1990, Scott Crump patented fused deposition modeling (FDM) 3D modeling (36).

Three-dimensional printing is an advanced technology in which digital models determined by CAD are printed (29-30-31). 3D printing, used in industry, engineering and various production areas, is also widely used in dentistry (32-33).

3D printing techniques are examined in three categories;

-Powder Bed Fusion

-Light Curing

-Fused Deposition Modeling

2.4.1 Powder bed fusion (PBF)

It is a 3D modeling method made by sintering powder material by grinding and fusing with a laser (37). There are four types of preinters according to the powder material and energy source used (38):

- Selective laser melting (SLM)
- Selective laser sintering (SLS)
- Electron beam melting (EBM)
- Direct metal laser sintering (DMLS)

In (SLM) and (EBM) techniques, metal powder is melted in an inert build chamber containing purified argon gas (39).

PBF is a preferred 3D modeling method in metal materials such as titanium implants used in dentistry, especially in implantology, prosthodontics and surgery.

2.4.2 Light Curing

Light curing is a 3D modeling method. The primary material of light curing is a photosensitive resin material, that is, shaped by curing with light radiation (40).

There are three types of printers with light curing:

- Stereolithography (SLA)
- Digital Light Processing (DLP)
- Photo Jet (PJ)

In SLA and DLP technologies, the printing process takes place in 3 stages:

--Light exposure

--Building platform movements

--Resin refilling

The equipment required for SLA three-dimensional modeling is:

- Reservoir containing photosensitive liquid resin
- The platform on which the model will be built
- UV laser source that will cure the resin

Immersed in the liquid resin, the platform moves vertically as each layer is formed and cured with a laser beam, allowing a new layer to form. With a mechanism that proceeds this way, this process continues until the model determined by software is formed (41).

DLP printers consist of a system of mirrors arranged in rectangles called digital micro reflector devices. Each mirror reflects a pixel. The number of mirrors depends on the shape of the projected object. The angles of the digital micro reflector must be adjusted one by one. The beam from the light source reflects on these micromirrors and projects it onto the surface to be printed as a pixel (38-42).

The advantage of DLP over SLA is that each layer is formed by a single laser irradiation, thus shortening the printing time.

Photopolymerizable (PJ) inkjet differs from the other two light-curing resins. During printing, the polymer is sprayed on the special table, and the layers cured with the UV lamp are formed on top of each other. Objects with different properties can be produced using different materials in inkjet-based 3D printers (43). Since this technique's surface quality is excellent, it does not require polishing.

2.4.3. Fused Deposition Modeling.

Filament-based printers:

According to the filament types used in 3D printers that produce models using filaments, the most common ones today are ABS and PLA filaments. The filament used in FDM printers, heated to a temperature just above the melting point, cools and hardens as soon as it leaves the nozzle tip, thus providing dimensional stabilization (31). The computer-controlled nozzle and worktable continue printing by moving along the x-y axis. The material accumulated in layers solidifies and forms the designed object. Due to the physical limitations of the nozzle, the outer surfaces of these models are rough since the layer produced at one time cannot be very thin. Due to this feature, the use of FDM printers is limited in places where the targeted object should be aesthetic and detailed. It is preferred because aesthetics and surface roughness are not crucial in orthodontic models. In orthodontics FDM printers are preferred because they are easy to use, they take up less space and are economical. Thermoplastic appliances are created by applying pressure and vacuum on these models, and some elasticity is required to remove the appliance from the model. The flexion and tension strengths of ABS and PLA have paved the way for their use in this application. (44)

Chen et al. have shown in their studies that the models printed on the FDM printer can be used instead of plaster models. (45)

Yefang et al. have shown in their studies that scaffolds produced from medical grade polycarpic acid-tensioned-tricalcium phosphate by the FDM method can be used in implant treatments in dentistry due to their biocompatibility and suitable mechanical properties (46).

2.4.3.1.ABS

ABS is a petroleum-based material made from acrylonitrile 1-3, butadiene styrene monomers. Models obtained from ABS show some shrinkage during cooling. Models produced from ABS filaments are preferred in fields such as toy production and engineering, as they have high resistance to vibration impact, shearing and tensile strength (31). It is possible to process ABS, such as post-processing, sandblasting, and painting. Since ABS melts with acetone, acetone welding can be performed (38). To compensate for the deficiencies in the mechanical properties of ABS, the composite filament is reinforced with graphene oxide to increase tensile strength and Young's Modulus.

2.4.3.2 PLA

PLA is a chemical biopolymer and thermoplastic produced from polylactic acid from sugar cane and corn starch. Therefore, it is not harmful to human health (biocompatible). PLA is immunologically inert. It is reduced to harmless lactic acid within 6 months to 2 years. Because of this feature, it has many uses in medicine. By the help of PLA's glassy phase transition temperature (Tg = 60-650C^0) and its melting point (Tm = 173-1780C^0), a heated table is not needed for printing.

Since PLA is biodegradable, it is among the environmental elements. Models with PLA-type filaments resist impacts but have slight flexibility and high brittleness. Models produced from PLA are preferred for products that come into contact with living beings, as they are not cytotoxic and do not contain harmful substances to health. The PLA filament has been upgraded with different materials to improve its morphological, chemical, structural, and mechanical properties and biocompatibility. PLA-GO (graphene oxide). (Nozzle temperature PLA: 3500 °F, ABS: 4500 °F) (31).

- Since ABS is processed at high temperatures, toxic gases are formed in the printing environment. There is no such problem with PLA, because it can be printed at lower temperatures.

- The heat resistance of ABS is higher than PLA. PLA distorts at 1200 °F temperature, while ABS lasts up to 2000 °F. For this reason, ABS is preferred in environments where the temperature can rise, such as computer and automobile technology. The moisture absorption of ABS is less than PLA's (31,32).

2.5. Factors Affecting Three-Dimensional Printing Products

We can examine the main factors affecting the accuracy, processing time, ultimate tensile strength, compression strength elasticity modulus, yield strength, impact strength and induced residual stress properties of the object produced with a 3D printer in 4 groups:

- Process parameters
- Material composition
- Post-processing
- Aging

2.5.1. Process parameters

Process parameters are examined under four categories, Build orientation, layer thickness, infill ratio, material composition.

2.5.1.1. Build Orientation

It refers to how a model should be positioned during the build process. Build orientation enables the reduction of support structures and affects the surface quality, accuracy, mechanical durability, and printing time of the designed model. It should be adjusted in the most appropriate way to meet the designed object's requirements (47-48-49).

2.5.1.2. Layer Thickness

It refers to the thickness of the layers used in printing and affects the printing result. Layer thickness is a property of the printer machine; it affects print quality, duration, and surface detail. As the layer thickness decreases, the resolution increases and a smoother surface is obtained. Decreasing of layer thickness, increases the printing time. Depending on the material's characteristics and the designed object's shape, the thinning of the layers provides a more homogeneous and resistant structure. The layer thickness is different for each printing technology.

Cheng et. al., in their study found that the production time was shortened as the layer thickness increased, but the accuracy decreased (50).

Chockalingam et. al. indicated that, the model's strength increases as the layer thickness decreases in models produced with the SLA technique (51).

According to Loflin et.al, 100-micrometer is the most appropriate thickness for orthodontic models (52).

2.5.1.3. Infill Ratio

This term expresses the ratio of the solid material to empty space in an 3D printed object. The variability of the infill ratio affects the strength and if sufficient, supports the model’s unity. As the percentage of infill increases, the strength and pressure resistance increase.

Infill is one of the most important factors, affecting the amount of material in 3D printing technology. When infill ratio increases, the printing time and the amount of material used have also increased.

The ideal infill ratio of the printer is determined by the air gap between the layers of the printed object. If the infill ratio is low, this can be compensated by careful design and construction. Bakir et.al. found that as infill increases, brittleness increases (53).

2.5.1.4. Raster Angle

This term indicates the angle between the printed grids in respect with the x-axis. It is usually between -90^0 to 90^0 (54).

2.5.2 Material Composition

It expresses the content and components of the material used in 3D modelling. Material composition affects the chemical and physical properties of the 3D model. The material used is critical in influencing the properties of the final product printed from the 3D printer and is chosen according to the intended use of the model. Many studies have shown that the added components change and improve the properties of the manufactured object (55).

One of the important criteria in material selection in the 3D printing process is the point at which the material undergoes plastic deformation. When a material undergoes plastic deformation that material has been permanently deformed. The point where the plastic deformation begins shows the material's strength and flexibility against the force on it. For this reason, transition points from elastic deformation to plastic deformation has utmost importance for the models produced in professions such as dentistry and engineering, where 3D modeling is frequently used.

2.5.3 Post-Processing

The polymerization and solidification processes made by UV light and thermal methods which take place after the 3D printing. It increases the resistance of the material and improves the surface quality. It ensures complete solidification of the model and cleaning of residual monomers in its internal structure. In SLA printer processes, disadvantages such as shrinkage and deformation in resin materials are eliminated by post-curing processes. When the resin object is exposed to a specific heat or UV and microwave for curing, the elastic modulus and strength of the object increase.

Jindal et al. found that the durability of aligners increased when post-cured with the heat between 40-800C^0 for 15-20 minutes, using a 405-nanometer light source (13 poly directional light-emitting diodes) (56).

2.5.4. Aging

It is the name given to a series of changes in the chemical structure and composition of polymer materials caused by environmental factors over time. These changes can cause transformations in the properties of materials. Elasticity modulus, ultimate tensile strength, flexural modulus and strength increase, and impact strength elongation at break decrease over time (57). Light-curing resins undergo dimensional changes at different temperature and humidity levels (58).

2.6. The Requirements of Three-Dimensional Materials

- Print speed and cost: The printing time should be as short as possible without compromising the quality of the printed object.
- Accuracy: All the details of the surface should be clearly transferred from the software to the 3D object.

- Strength: It is the resistance of the 3D model to the force applied on it.
- Measurement precision: The dimensions of the digitally designed object should be the same as the printed objects dimensions. The sensitivity in the printing process and the printer's calibration closely affects this parameter.
- Material compatibility: Material must be selected according to the manufacturer’s recommendations.
- Biocompatibility: The materials used, and the printing procedures should not be harmful to the health of living beings.
- Environmentally compatible: The model materials shouldn’t harm the environment. Recyclable materials should be preferred. For example, PLA filament are environmentally friendly products.

The drawbacks of the plaster models such as breaking, occupying too much space are eliminated by the introduction of the 3D modeling in orthodontics (59). Oral scanners, portable cameras, computers can be used for digital recording.

Today's five most popular printing technologies are FDM, PJ, SLA, SLS and DLP (60).

The superior features of 3D dental models over plaster dental models are that they are lighter, durable, long-lasting and can easily be shared. In addition, printing from environmentally friendly materials is possible (61).

Jeong et al. found that 3D printed models have higher accuracy and reproducibility than traditional plaster models (62).

Studies have determined that the reproducibility and accuracy of 3D models are higher than traditional modeling methods, but this difference does not have any significance in orthodontic treatment planning (63-64).

In their study, Hazeveld et al. found that the models produced in DLP printers are more accurate than other 3D printers (65)

3. MATERIALS AND METHOD

The study is planned in two main groups of 3D materials: ABS group and Resin group. The chemical structure and brand names of the two main groups are listed in Table 1. Each sub-group contains 10 pieces of specimen which are digitally designed to be 30%, 60% 80% and 100% ratio (Table 2).

Table 3. 1. Materials used in the research and their chemical structures.

Groups:	Brand	Chemical structure
ABS	eSUN ABS+	acrylonitrile, 1-3, butadiene styrene
RESIN	Anycubic standard 3d printing resin	(1-methyl-1,2ethanediyl)bis[oxy(methyl-2,1-ethanediyl)] diacrylate

Table 3. 2. Number of samples:

	30%	60 %	80 %	100%
ABS	10	10	10	10
Resin	10	10	10	10

3.1 Sample

In this study, the compressive strength of the rectangular prism-shaped samples produced from ABS filament and resin material at different infill ratios are determined and compared: (Table 3, Table 4)

Two main groups were created.

- Group A: ABS filament
    - 30% infill – 10 pieces
    - 60% infill – 10 pieces
    - 80% infill – 10 pieces
    - 100% infill – 10 pieces

- Group B: Resin
- 30 %infill – 10 pieces
- 60% infill – 10 pieces
- 80% infill – 10 pieces
- 100% infill – 10 pieces

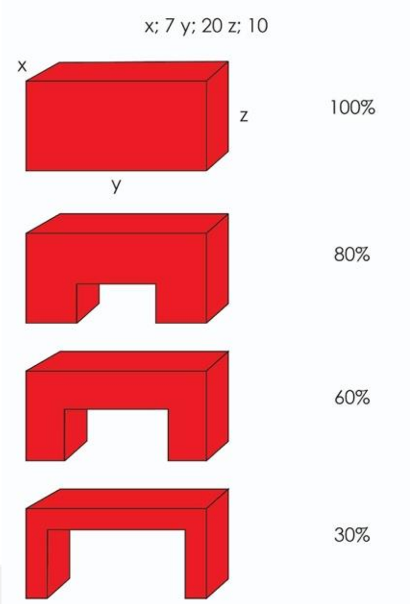
3.2. Sample Size

In this study, a total of 80 samples have been used. Two main groups have been formed from two different materials. Four subgroups have been formed according to infill ratios. Samples in the ABS group are shown in red, and the ones in the resin group in green. In the power analysis performed with the G*power 3.1 program related to our study, the sample size of each study group was found to be 10.

3.3. Preparation of the FDM Printer and the Production of Filament (ABS) Blocks

Samples in the form of rectangular blocks with dimensions 7mm x 10mm x 20mm with 30%, 60%, 80% and 100% infill ratios have been digitally designed using the 'UltiMaker Cura' software. Block designs were exported in STL. extension. The designed files were divided into layers using a software program called ‘Anycubic Slicer V26’. The desired movements of the nozzle of the 3D printer were converted into a digital data called G-code. An ABS filament spool is attached to the back of the FDM printer. The tip of the printer, ‘nozzle’, was raised to a temperature of 240^0C-250^0C. The filament moved towards the nozzle. The nozzle with the molten filament inside started to make the movements specified in the G-code and pushed the filament toward into the print bed. Reaching the print bed, the filament cooled immediately, maintaining its dimensional stability.

The final product was removed from the print bed. After the cooling down of the blocks, the supporting structures were severed and separated. Residual filament particles were removed with a hand brush and washed with water. The prepared samples were measured with a digital caliper. Samples that did not match the planed dimensions were excluded from the study.



Scheme 3. 1. Digitally designed models of the ABS blocks

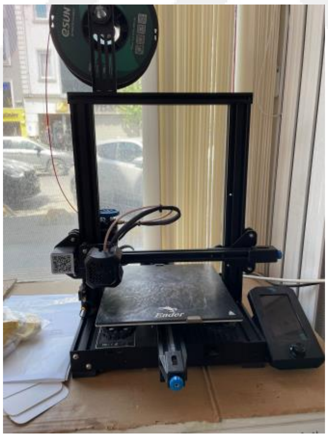
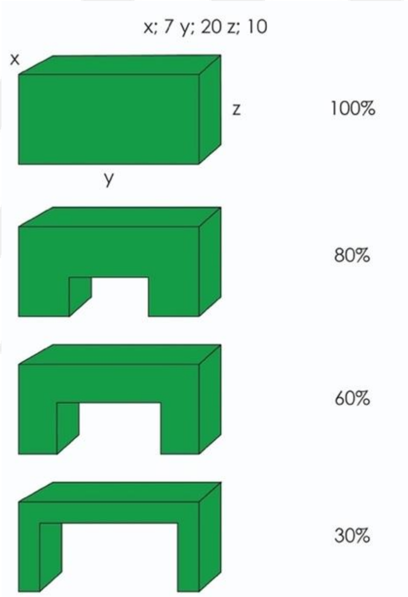


Figure 3. 1 . FDM type 3D printer (Creality Ender-3 S1 Pro)

3.4. Preparation of the DLP printer and the Production of Resin Blocks

Samples in the form of rectangular blocks with dimensions 7mmx10mm x20mm with 30%, 60%, 80% and 100% infill ratios have been digitally designed using the 'Anycubic Photon Mono X ' software. Block designs were exported in STL. extension. Through the Anycubic Slicer V26 program, the designed file was divided into layers.

The print bed has been cleaned. The resin tank was filled with 'Anycubic Standard 3D Printing Resin'. The printing process has been started on the 'Anycubic Photon Mono X' brand DLP type printer. Layers began to form on the print bed, and the bed descended to make room for new layers. A chemical bond was formed between its layers. The resin was then cured. After this process was finished, the sample was washed with isopropyl alcohol in a closed plastic box for fifteen minutes so that the resin burrs on the outer layer were removed. The resin was cured by exposure to a UV light source. By repeating this process, sample blocks were created. The prepared samples were measured with a digital caliper. Samples that did not match the planned dimensions were excluded from the study.



Scheme 3. 2. Digitally designed models of the resin blocks

Figure 3. 2. DLP type, 'Anycubic Photon Mono X' brand 3D printer

3.5. Strength Test Preparation and Application

The samples were placed on the table of the Instron (3345) Universal Testing Machine. Using ‘Instron Bluehill 3 software’, the crosshead applied a point force to the blocks' center point at a 3mm/min velocity. The application of force continued until the first cracking was observed in the blocks. At that moment the Instron Universal Testing Machine was manually stopped. The pressure values at that moment were recorded in the software program being used.

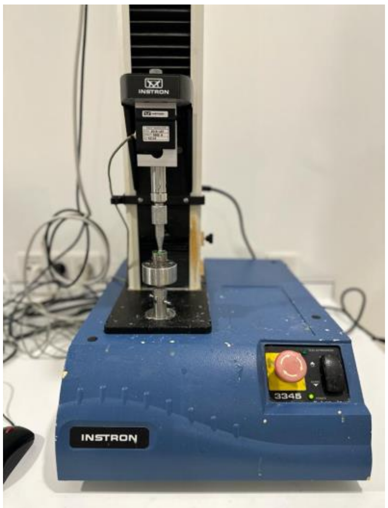


Figure 3. 3. Instron 3345 (Universal Testing Machine)

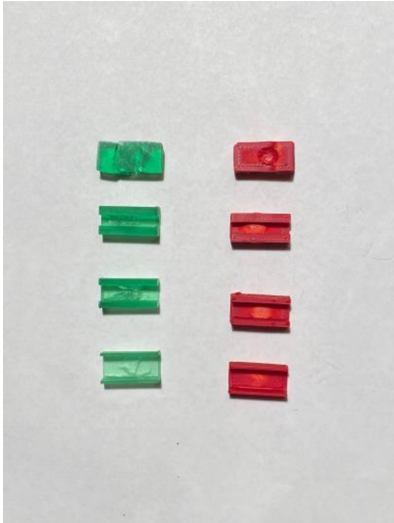


Figure 3. 4. ABS and Resin blocks used in this experiment.

3.6. Statistical Analysis

The values obtained from the statistical evaluations were made with the NCSS (Number Cruncher Statistical System) 2007 Statistical Software (Utah, USA) package. In the evaluation of the data, besides descriptive statistical methods (mean, standard deviation), the distribution of the variables was examined with the Shapiro-Wilk normality test, a two-way analysis of variance was used in the comparisons of the normally distributed variables, and the Tukey 's multiple comparison test was used in the subgroup comparisons. The results were evaluated at the significance level of $p<0.05$.

4. RESULTS

The maximum load values that ABS and resin block samples can withstand during compressive strength were compared according to their infill ratios. In this comparison, ten samples were tested for each group.

When the results for ABS blocks were examined, it was seen that the maximum load values at the compressive strength were different in the groups with %30, %60, %80 and %100 infill ratios. The results are given in Table 4.3.

Table 4. 1**.** Maximum load at compressive strength for ABS blocks according to infill ratio.

ABS	Maximum Load at Compressive Strength (MPa)			
	30%	**60%**	**80%**	**100%**
1	1.650	11.682	24.579	25.407
2	2.267	13.139	27.681	26.184
3	2.126	12.230	27.249	25.806
4	2.291	12.477	27.322	25.272
5	1.517	12.851	28.615	26.087
6	1.837	12.797	25.068	27.191
7	1.802	14.373	26.517	24.240
8	1.661	12.341	27.844	26.028
9	1.929	11.050	25.711	25.877
10	1.336	13.380	27.342	26.246

When the results for the resin blocks were examined, it was observed that the maximum load values at the compressive strength were different in the groups with %30, %60, %80 and %100 infill ratios. The results are given in Table 4.4.

Table 4. 2. Maximum load at compressive strength for resin blocks according to infill ratio

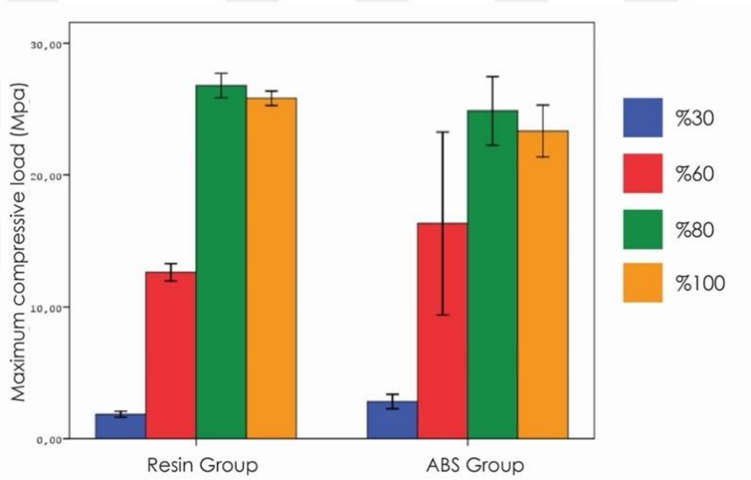
Resin	Maximum Load at Compressive Strength (MPa)			
	30%	**60%**	**80%**	**100%**
1	2.335	15.946	29.687	20.524
2	2.238	15.036	19.602	23.899
3	2.394	43.348	23.161	24.876
4	2.246	13.750	27.270	19.844
5	2.460	10.396	24.461	23.261
6	3.651	14.758	23.091	26.257
7	4.397	12.377	20.835	19.623
8	3.601	11.345	27.285	26.717
9	2.401	15.083	30.406	21.883
10	2.378	11.211	22.822	26.556

The ABS groups were compared with each other according to their infill ratios; the results are shown in Table 4.5 and Scheme 4.3. The maximum average loads at the compressive strength of the group with 30% infill ratio was statistically significantly lower than the groups with 60%, 80% and 100% infill ratio (p=0.0001). The maximum average loads at the compressive strength of the group with 60% infill ratio was statistically significantly higher than the groups with 80% and 100% infill ratio (p=0.0001). No statistically significant difference was observed between the maximum load averages in the compressive strength of the groups with 80% and 100% infill (p=0.097).

The resin groups were compared with each other according to their infill rates; the results are shown in Table 4.5 and Scheme 4.3. A statistically significant difference was observed between the averages of maximum load in the compressive strength of the 30%, 60%, 80% and 100% infill ratio groups of the resin group (p=0.0001). As seen in Table 8, the maximum load averages at the compressive strength of the 30% infill ratio group were statistically significantly lower than the 60%,80% and 100% infill ratio groups (p=0.0001). The maximum average load at the compressive strength of the 60% infill ratio group was statistically significantly higher than the 80% and 100% infill ratio groups (p=0.0001). No statistically significant difference was observed between the maximum load averages in compressive strength of 80% and 100% infill ratio groups (p=0.921).

Table 4. 3. Tukey's Multiple Comparison Test

Tukey's Multiple Comparison Test	ABS Group	Resin Group
30% Infill / 60% Infill	0.0001	0.0001
30% Infill / 80% Infill	0.0001	0.0001
30% Infill /100 % Infill	0.0001	0.0001
60% Infill / 80% Infill	0.0001	0.006
60% Infill / 100% Infill	0.0001	0.029
80% Infill / 100% Infill	0.097	0.921



Scheme 4. 1 . Comparison of compressive resistance of ABS and Resin group infill ratios

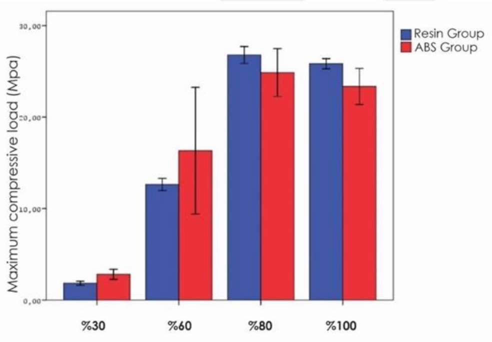
A statistical evaluation of comparing ABS and resin groups with each other at the same infill ratios was made. The results are shown in Table 4.6, Scheme 4.3. and 4.4. Maximum load averages at the compressive strength of the resin group at 30% infill ratio were statistically significantly higher than the ABS group (p=0.002). No statistically significant difference was observed between the maximum load averages in the compressive strength of ABS and resin groups at 60% infill ratio (p=0.246). No statistically significant difference was observed when the maximum load averages were compared in the compressive strength of ABS and resin groups at 80% infill ratio (p=0.132). The maximum load averages at the compressive strength of the resin group at 100% infill ratio were statistically significantly lower than that of the ABS group (p=0.002).

As seen in Table 4.6, a statistically significant difference was observed between the maximum load averages in the compressive strength of the 30%, 60%, 80% and 100 % infill ratio groups of the ABS and Resins groups (p=0.0001).

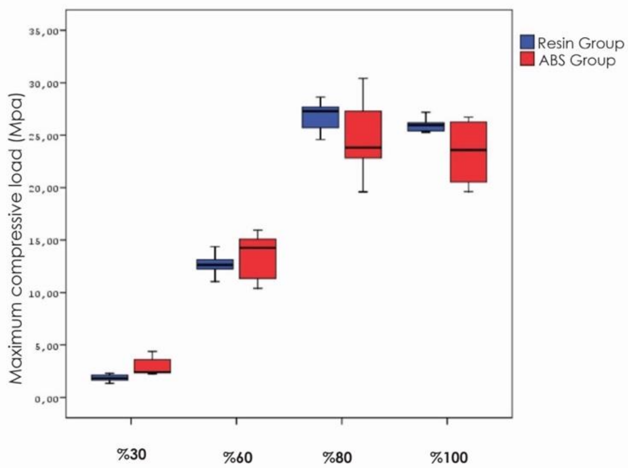
Table 4. 4. Statistical evaluation of the intergroup comparison of compressive strengths

	ABS Group	Resin Group	p-value*
30% Infill	1.84±0.32	2.81±0.77	**0.002**
60 %Infill	12.63±0.92	16.33±9.69	0.246
80% Infill	26.79±1.30	24.86±3.65	0.132
100% Infill	25.83±0.77	23,34±2.77	**0.013**
p-value‡	**0.0001**	**0.0001**	

‡ One-Way Analysis of Variance (ANOVA) *Independent t-test



Scheme 4. 2. Comparison of the maximum loads at compressive strengths of resin and ABS groups at different infill ratios



Scheme 4. 3. Bar graph of maximum loads at compressive strength of ABS and resin groups

5. DISCUSSION

This study which compares the mechanical properties of 3D printed orthodontic models with different materials and infill patterns aims to provide contribution to the advancement of 3D printing technologies in aligner therapy in orthodontics.

3D models which do not plastically deform during thermoforming procedures are the main tools of aligner production.

Time saving and cost reducing effect of printing 3D models with the minimum model material that fulfill the requirements of thermoforming is also an environmentally friendly attempt.

The study by M. Zeng et al. in 2017 shows a significant reduction in chair time and treatment duration in mild to moderate cases in treatments with clear aligners (66).

Skidmore et al., in their study, determined that the duration of treatment depends on the patient's characteristics, expectations and treatment decisions (67). And Royko et. al. reported that compliance is higher when the treatment period is shorter (68).

The innovation of CAD-CAM technology emphasizes the importance of printers in the production of clear aligners (69).

Nowadays as direct printed aligner technology is spreading rapidly, the need to use dental models in aligner production may decrease. Direct printed aligner technology has disadvantages such as high cost, space-consuming tools and releasing harmful chemicals into the environment during production (23-24-25).

In 2023 Panayi emphasized, orthodontic associations should build a protocol which takes control of the toxic and irritating effects of the released chemicals in dental clinics during direct printed aligner production (69).

This study may contribute to environmental awareness by reducing the use of plastic material used for 3D model making.

Tartaglia et. al., in their study in 2021, reported that the cytotoxicity and biocompatibility of the production of direct 3D printed aligners should be compared with those produced by thermoforming ones (70). Francisco et. al., in their systematic review titled "The biological effects of 3D resin used in orthodontics" in 2022, determined that 3D printed aligners were more cytotoxic and genotoxic than thermoplastic resins (71).

This study compared samples made of polymer-based ABS and resin, produced with two different printing methods, FDM and DLP.

The reasons for choosing ABS (Acrylonitrile, 1-3, butadiene styrene) as one of the materials in this study were its economic suitability, high heat resistance and high strength (72). Ease of production and supply is another reason for preference. In the studies made with FDM printers, ABS filaments are frequently used, which enables us with a lot of source materials for information.

The resin test blocks are obtained from a polymer, based on methyl methacrylate, which is a thermoplastic resin. This chemical substance is also widely used in various branches of dentistry. We preferred a cross-linked methyl methacrylate resin in our study because these resins are more resistant to compressive forces. Thermoplastic resins are easily deformed under pressure, and cross-links can minimize deformation. The chemical composition of the resin we use is "(1-methyl-1,2-ethanediyl) bis[0xy(methyl-2,1-ethanedyl)] diacrylate". The resin we use is a one-component flowable resin (73). This material is transparent and biocompatible. It is resistant to the forces of the vacuum formed by the thermoforming procedure during aligner production. One of the reasons for choosing the resin in this study is that it can withstand temperatures of approximately 180-200 °C during the thermoforming process (74).

In this research, we worked on 30%, 60%, 80%, 100% filled, rectangular prism-shaped specimens, that were digitally arranged by the help of the software 'UltiMaker Cura'.

We chose the Instron Universal Testing Machine in this study because it imitates the measurable vertical force, similar to the force exerted by the thermoforming machine on the models during aligner production.

The sudden numerical changes that we recorded during the experiment indicates the point where the plastic deformation begins (75). When the plastic deformation occurs, the model material has gone an irreversible structural change, so it goes beyond its original production purpose. In this experiment maximum compressive strength values were recorded in order to evaluate the optimum model material and infill percentage.

The test results of the two groups and eight subgroups have been statistically evaluated. Considering that the compressive force required for orthodontic aligner production is around 0.4 MPa, all the groups in our study fulfill the requirements for 3D orthodontic model production. The compressive strength of all groups (30%, 60%, 80%,100 %) is over 0.4 MPa.

The resin group at 80% infill percentage has the highest compressive strength as seen on Scheme 4.3. and Table 4.6.

In both groups the compressive strength of the 100% infill percentage sub-group is less than 80% percentage sub-group (Scheme 4.4. and Table 4.5.). This result shows that the compressive strength doesn't increase directly proportional with infill percentage. Various internal structural factors are affecting the model materials compressive strength. The transition to plastic deformation in the 100% infill sub-group was earlier than in the 80 % infill sub-group. This unexpected result is caused by the increasing of stiffness and brittleness as the infill percentage increases (53). In the 100 % sub-group as the air gaps between the layers decrease the object's stiffness increases. As the stiffness increases, the flexibility decreases (51,75).

Sung-Hoon et al., reported that the decrease in the gaps between the layers of the printed object creates a negative air gap. As a result, the strength and stiffness increase. The same study stated that raster orientation also affects compressive strength (77).

Luzanin et al. reported in their study that the compressive strength of the object in FDM modeling depends on its density. The air gap and infill parameters influence the object's density. In the experimental with samples at 10 % and 30 % infill values, it was reported that when the layer thickness, deposition angle and infill values decrease the printing speed increases (78).

The build orientation of a 3D-printed object is one of the important constructional properties, affecting its resistance to compressive forces. Considering this information, the sample blocks were printed so that the large surfaces of the prism facing the print bed.

Kasper who emptied horseshoe shaped models, imitating alveolar arches in his research, reduced the printing time and the amount of material used. He found out that the design of the 3D models affects the printing time, used material amount and also other physical properties of the model (79). In this study to produce 3D models with the least amount of material to increase the financial productivity and time efficiency we used various digitally emptied models for the same purpose to test their compressive force resistances.

The printing time of resin is longer than ABS, and as the infill ratio decreases in both materials, print speed increases. Therefore, we did not find it necessary to evaluate the time factor in our study.

Masiuchok et al., in their study titled "Comparative Analysis of The Quality of Plastic Products Formed by DLP and FDM Printing Technologies", published in 2020, compared the layer formation durations of DLP and FDM printers. This study demonstrated the speed superiority of FDM printers over DLP printers (80).

The compressive strength of resin is higher than ABS at infill rates higher than 60%, contrary to what is seen at lower than 60% infill percentage (Scheme 4). This may be because the resin material gets more flexible than ABS as the infill rate increases. This finding, which states that the brittleness of ABS sample blocks increases as the infill rate increases, can be explained by the internal structure differences of the materials (81).

Tanveer et. al. showed in their study that flexural strength of a model is determined by its layer thickness, deposition angle and infill parameters. The limit of the compressive force applied on the model depends on the model’s flexural strength (81).

Sofu et. al. determined that in FDM technology, the density of the model is determined by air gap and infill parameters. They point out that, having a low infill value is also a factor that increases the speed and reduce the cost of printing procedures (82).

According to the first rule of thermodynamics ‘principle of conservation of energy’, the thermal energy generated during thermoforming makes a dimensional change in the model mass. Since the heat conduction coefficients of resin and ABS materials are low, while filling rates of the models are high, the effect of thermal deformation during thermoforming is negligible (83).

As the infill rates decrease, the thermal deformation that occurs in the model may reach undesirable levels for aligner printing. For further studies carried out with specimens under 30 % infill ratios, the effect of the high temperature during thermoforming process should be examined with the compressive strength.

6. CONCLUSION

- Based on the behavior of the two materials, the result obtained can be used to generate data about their use in model construction.
- Following the findings of this investigation, all percentage groups are appropriate for 3D dental model production because the compressive force applied when printing clear aligners is around 0.4 MPa.
- When ABS and resin groups with 80% and 100% infill were compared, the compressive strength of the groups with 80 % infill was higher than 100% in all groups.
- At 60 % infill and below, resin material samples have lower compressive strength whereas over 60 % infill levels, ABS filament specimen have a lower compressive strength.
- 80 % resin samples have the highest compressive strength compared to all other groups.
- Similar studies should be conducted in groups with an infill percentage below 30%. High temperature of the thermoforming process should be taken into consideration.
- To obtain usable results, experiments on samples with various print parameters should be carried on. (Build orientation, infill pattern, raster angle, layer thickness).
- For the data we have obtained to be usable, our study should be supported by new studies using models that can best imitate dento-alveolar arch form in terms of design.

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8. CURRICULUM VITAE

Kişisel Bilgiler

Adı	Yavuz Deniz	**Soyadı**	Tankuter
Doğum Yeri		**Doğum Tarihi**	
Uyruğu		**TC Kimlik No**	
E-mail		**Tel**	

Öğrenim Durumu

Derece	Alan	Mezun Olduğu Kurumun Adı	Mezuniyet Yılı
Doktora		**Yeditepe Üniversitesi**	
Lisans		**Yeditepe Üniversitesi**	
Lise		**Üsküdar Amerikan Lisesi**	

Bildiği Yabancı Dilleri	Yabancı Dil Sınav Notu (#)
İngilizce	

Başarılmış birden fazla sınav varsa(KPDS, ÜDS, TOEFL; EELTS vs), tüm sonuçlar yazılmalıdır

İş Deneyimi (Sondan geçmişe doğru sıralayın)

Görevi	Kurum	Süre (Yıl - Yıl)
		-
		-

Bilgisayar Bilgisi

Program	Kullanma becerisi

***Çok iyi, iyi, orta, zayıf olarak değerlendirin**

Bilimsel Çalışmaları

SCI, SSCI, AHCI indekslerine giren dergilerde yayınlanan makaleler

Diğer dergilerde yayınlanan makaleler

Uluslararası bilimsel toplantılarda sunulan ve bildiri kitabında (*Proceedings*) basılan bildiriler

Hakemli konferans/sempozyumların bildiri kitaplarında yer alan yayınlar

Diğer (Görev Aldığı Projeler/Sertifikaları/Ödülleri)