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Comparison of mechanical properties of polyethylene and polyurethane blocks as model materials for in vitro cortical bone modelling

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ABSTRACT

Aims: The aim of this study was to compare polyethylene (PE) and polyurethane (PU) blocks at a density of 60 pcf in terms of flexural strength (FS), elastic modulus (EM), elongation, and hardness in vitro for use in cortical bone modelling.

Methods: This in vitro study was conducted at Van Yüzüncü Yıl University Faculty of Dentistry Department of Orthodontics and the testing and laboratory phases of the study were conducted at Van Yüzüncü Yıl University Faculty of Dentistry Research Laboratory. PE (group 1) and PU (group 2) blocks with a density of 60 pcf (0.96 g/cm^3) were used in the study. The 3-point bending test was performed on a universal testing machine and FS, EM, elongation, and hardness were measured. A total of 30 samples, 15 in the PU group and 15 in the PE group, were included in the study.

Results: The FS and hardness values of PE and PU did not show statistically significant differences ($p>0.05$). Statistically significant differences were found between the PE and PU groups for EM and elongation values ($p<0.05$).

Conclusion: This study showed that PE blocks can be used in orthodontics for in vitro cortical bone modelling.

Keywords: Polyethylene block, polyurethane block, cortical bone, orthodontics, flexural strength, elastic modulus

INTRODUCTION

In recent years, it has been observed that many materials and devices used in the oral and maxillofacial region are polymer-based. The reasons for the preference of polymers are their biocompatibility and the fact that their mechanical properties meet the requirements of the region in which they will be used. Polyethylene (PE) is a versatile and adaptable biomaterial that is widely used in in vitro and in vivo studies.[1] PE is preferred because of its low cost, chemical inertness, good electrical properties, and relative ease of processing.[2] In the medical sector, it is used in the manufacture of disposable or reusable medical devices and in the production of various implants.[3]

Polyurethane (PU) is another synthetic polymer with a wide variety of chemical compositions and properties that are used in many areas of our daily lives.[4] Again, due to the rapid developments in biomaterials used in prostheses and medical devices in recent years, PU has started to be widely used in the medical field due to its mechanical properties and excellent biocompatibility.[5] The PU bone model, which can be prepared in different densities and microstructures, can mimic human bone and the mechanical and physical properties of the cortical and cancellous bone components.[6]

PU bone models allow standardization of biomechanical evaluation in in vitro studies due to their homogeneous structure. PU sheets with different densities are available to simulate different bone types and these sheets are often used as bone models in in vitro studies of orthodontic mini-implants. In the literature, PU sheets with densities of between 40 and 50 pcf have been used to simulate cortical bone.[7,8] Although PE is widely used in the medical field due to its structural properties, there is no study in the literature using it as a bone model material. Presenting data to support what type of bone PE can be used for modelling in vitro studies will pave the way for the use of PE for this purpose. PE sheets with a density of 60 pcf are currently available on the market. With regard to the use of PU sheets with a density of 60 pcf for modelling cortical bone, we believe that it would be more accurate and valuable to compare the mechanical properties of PE sheets of the same density with the mechanical properties of a polymer such as PU, which is accepted in the literature as a reference for its mechanical properties in in vitro modelling of cortical bone. The aim of this study was to compare PE and PU blocks at a density of 60 pcf in terms of flexural strength (FS), elastic

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modulus (EM), elongation and hardness in vitro for use in cortical bone modelling. The null hypothesis of the study was that there would be no difference in flexural strength, modulus, strain and hardness between 60 pcf PE blocks and 60 pcf PU blocks.

METHODS

Ethics committee approval is not required since this study was conducted on polyethylene and polyurethane blocks in the laboratory. All procedures were carried out in accordance with the ethical rules and principles.

This in vitro study was conducted at Van Yüzüncü Yıl University Faculty of Dentistry and the testing and laboratory phases of the study were conducted at Van Yüzüncü Yıl University Faculty of Dentistry Research Laboratory. PE (group 1) (Simitçioğlu Metal Stainless Construction Industry and Trade Limited Company, İstanbul, Turkiye) and PU (group 2) (Quantum Polyurethane Machine Material Industry Trade Limited Company, Bursa, Turkiye) sheets with a density of 60 pcf (0.96 g/cm^3) were used in the study. The literature indicates that the flexural strength of the material is generally measured when evaluating the mechanical properties of polymeric materials. Therefore, it was decided to measure the flexural strength of PE and PU to evaluate their mechanical properties in this study. The three-point flexure test, which is one of the uniaxial tests used for the flexural strength of polymers and plastics, was preferred for the evaluation of mechanical properties.[9] The materials to be tested with the 3-point flexure test have to be prepared to a certain standard size for standardization. For this reason, the PE and PU blocks used in the study were prepared according to the ISO 178 standard with a length of 80 mm, a width of 10 mm, and a thickness of 4 mm (**Figure 1, 2**).[10]

Figure 1. Polyethylene block prepared in the dimensions 4x10x80 mm

Figure 2. Polyurethane block prepared in the dimensions 4x10x80 mm

The 3-point bending test was performed on a universal testing machine (Shimadzu AGS-X, Shimadzu Corporation, Kyoto, Japan) (**Figure 3**).

Figure 3. Universal test device used in the study

The length, width, and thickness data of the PE and PU blocks were recorded on the Trapezium X materials testing software (Shimadzu Corporation, Kyoto, Japan) integrated with the universal testing machine (**Figure 4**).

Figure 4. Trapezium X materials testing software compatible with Universal testing machine

The distance between two supports in the universal testing machine was set at 40 mm. The force was applied from the center of the blocks at a rate of 1 mm/min. Using these parameters, a 3-point flexural test was performed on the universal testing machine (**Figure 5, 6**). The blocks in both groups were tested under the same humidity and temperature conditions.

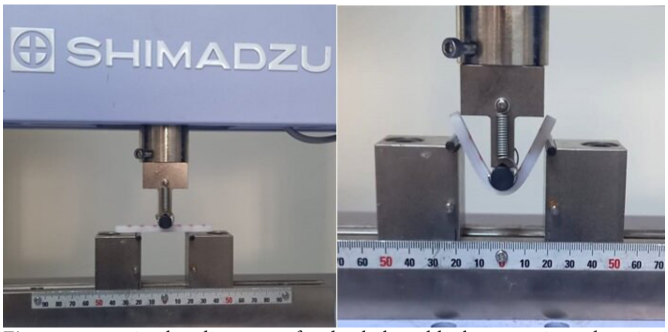

Figure 5. 3-point bending test of polyethylene blocks on universal testing machine

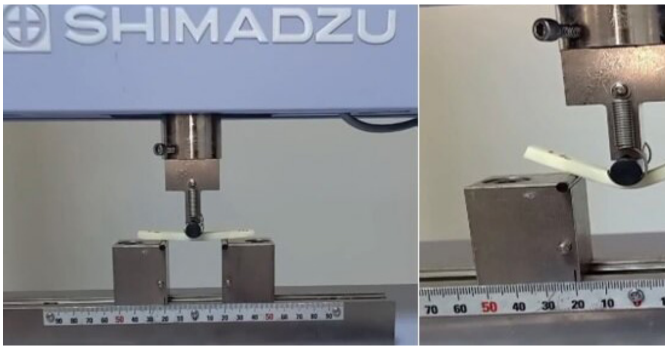

Figure 6. 3-point bending test of polyurethane blocks on universal testing machine

The flexural strength values obtained as a result of the test were recorded in Newtons and the elongation values were recorded in mm. The values obtained were converted to MPa in accordance with ISO standards. The elastic modulus, stress, and strain values were calculated using the following formulae.

The stress-strain formula was used to calculate the elastic modulus.

- Stress (MPa) = 3LF/2WT2
- L (mm) = Distance between two supports
- F (n) = Force
- W (mm) = Width of the block
- T (mm) = Thickness of the block
- Strain L0 (amount of elongation) / L (original length).[11]

A digital durometer (Shore D Durometer, Digital ShoreMeter DJD, Loyka Instruments, Turkiye) with an accuracy of 0.5 HD in the range of 0-100 HD was used to measure the surface hardness. Three different points from the surface of each block were measured and the average value obtained was used for the hardness measurement.

In one study in the literature evaluating flexural strength, the effect size was calculated to be 1.57. In accordance with the reference parameters, the sample size for this study was calculated using G*power (version 3.1.9.6) as d=1.57, power=0.95, α=0.05 with a 95% confidence interval, and a minimum of 13 samples for each group.[12]

Statistical Analysis

Data analyses were performed using SPSS 24.0. To determine the suitability of the quantitative values for normal distribution, the normal distribution condition was examined and kurtosis and skewness coefficients were calculated. Kurtosis and skewness values between +3 and -3 are considered sufficient for normal distribution.[13] Quantitative variables in this range are normally distributed (skewness /kurtosis coefficients are within limits) and therefore parametric methods were used in the analyses of strain, FS, EM, and hardness values in this study (**Table 1**). Independent groups t-test was used to compare groups and the significance level was p<0.05.

Table 1. Coefficients of skewness and kurtosis of the elongation, FS, EM, and hardness values of the blocks

	Skewness	Kurtosis
Elongation (mm)	-0.427	-0.187
Flexural strength (MPa)	0.763	1.912
Elastic modulus (MPa)	1.097	0.731
Hardness	-0.373	-0.557

FS: Flexural strength, EM: Elastic modulus, mm: Milimeter, MPa: Megapascal

RESULTS

A total of 30 samples, 15 in the PU group and 15 in the PE group were included in the study. During the tests, all the blocks in the PU group broke, while all the blocks in the PE group bent without breaking.

When the amount of elongation was analysed, it was found that the PU group elongated an average of 6.30±1.13 mm and the PE group elongated an average of 8.48±0.96 mm. When the elongation amounts of the PU and PE groups were compared, the difference between the elongation amounts was statistically significant and the elongation amount of PE was higher (p=0.000, p<0.001) (**Table 2**).

Table 2. Comparison of elongation, FS, EM, and hardness values between groups

	Polyurethane				Polyethylene				
	Min	Max	Mean	SD	Min	Max	Mean	SD	p
Elongation (mm)	3.571	8.514	6.3	1.13	5.82	9.977	8.48	0.96	0.000*
Flexural strength (MPa)	48.375	100.125	74.8	16.53	60	124.5	77.85	15.16	0.603
Elastic modulus (MPa)	383.2	1239	822.55	240.42	465.63	1426.25	631.2	228.02	0.033*
Hardness	74	79	76.7	1.64	74	78	76.4	1.17	0.643

p<0.05, *Independent groups T test, FS: Flexural strength, EM: Elastic modulus, Min: Minimum, Max: Maximum, SD: Standard deviation, MPa: Megapascal

When the FS was analysed, the FS of the PU group was calculated to be 74.80±16.53 MPa, while the FS of the PE group was calculated to be 77.85±15.16 MPa. When the FS values of the PU and PE groups were compared, it was found that there was no statistical difference between the two groups in terms of FS values (p=0.603, p>0.05) (**Table 2**).

When the EM was analysed, it was found that the EM of the PU group was 822.55±240.42 MPa, while the EM of the PE group was 631.20±228.02 MPa. When the EM values of the PU and PE groups were compared, the difference between the two groups was statistically significant and the EM of the PU was higher (p=0.033, p<0.05) (**Table 2**).

When hardness was analysed, the mean hardness of the PU group was 76.7±1.64 and the mean hardness of the PE group was 76.4±1.17. When the hardness values of the PU and PE groups were compared, it was found that there was no statistical difference between the two groups in terms of hardness values (p=0.603, p>0.05) (**Table 2**).

DISCUSSION

This study investigated the mechanical properties of PE and PU blocks and found that there was a difference between PE and PU blocks in terms of elongation and elastic modulus. Therefore, the null hypothesis of the study was accepted for flexural strength and hardness but rejected for elongation and elastic modulus. Misch et al.[14] showed that the mean elastic modulus of mandibular bone including cortical bone was 96.2 MPa, whereas the mean elastic modulus of mandibular bone excluding cortical bone was 56 MPa. Shash et al.[15] showed that the mean elastic modulus of cortical bone was 13.7 GPa. Arendts and Sigololto found the elastic modulus of mandibular bone to be 17.3 GPa[16] and Dechow et al.[17] 19.4 GPa. Stoppie et al.[18] found an elastic modulus of 374.51 MPa in both maxillary and mandibular specimens containing both cortical and trabecular bone. In the samples where only trabecular bone was evaluated, this value was 342.26 MPa. It can be seen that the reason for the difference in modulus between studies is due to the cortical and trabecular content of the region from which the sample was taken. It is understood that where there is more cortical bone, the elastic modulus will be higher. Misch et al.[14] found that the mean elastic modulus of mandibular trabecular bone was 56 MPa. In this study, the mean elastic modulus of PU was 822.55 and that of PE was 631.2 MPa. These values show that the elastic modulus of the 60 pcf density PE and PU used in this study is higher than the elastic modulus of trabecular bone. Therefore, when the elastic moduli obtained from the 60 pcf density PE and PU blocks used in this study are compared with the results of the aforementioned studies, it can be seen that both blocks are close to cortical bone in terms of EM. In the present study, it was observed that the amount of elongation of the PE blocks was higher than the amount of elongation of the PU blocks. The higher amount of elongation indicates that PE has a more flexible structure. The reason for the lower modulus of the PE blocks is that the amount of elongation of PE is higher. Young's modulus values of 60 pcf density PE blocks support the use of these blocks for in vitro modelling of cortical bone.

In mini-implant studies, PU blocks are used instead of bone.[19] It is generally not possible to perform studies to evaluate the characteristics of orthodontic mini-implants such as length, diameter, head-neck-body design, surface structure, and implant material in the clinical setting.[20,21] In addition to the difficulty of clinical evaluation of these bone-related studies, there are many standardization and ethical issues. In particular, PU blocks are preferred due to their homogeneous structure, bone-like mechanical properties, availability of different densities, and ease of use.[7] ASTM (American Society for Testing and Materials) has confirmed that rigid PU blocks are an ideal material to use as a bone substitute in in vitro studies of mini-implants.[22] Therefore, we selected PU blocks as one of our study groups in this study.

In some studies, PU blocks of different densities are used to model different bone types. Researchers prefer to use the PU block with a density that matches the structural properties of the bone being modelled.[23] It can be seen that PU blocks used to model cortical bone are preferred at densities of 30 pcf and above. Marchi et al.[8] compared the insertion torques of self-drilling mini-implants in different types of bone created in vitro. The authors preferred PU blocks of 40 and 50 pcf density for modelling cortical bone. Elibol et al.[24] evaluated the effect of cortical bone thickness and density on the stability of mini-implants and used 40, 45, and 50 pcf density PU blocks to model cortical bone. They preferred 25 pcf density PU blocks for modelling trabecular bone. Möhlhenrich et al.[19] investigated the effect of bone density on the stability of mini-implants. The authors preferred PU blocks with a density of 40 pcf for D1 bone, 30 pcf for D2 bone, 20 pcf for D3 bone, and 10 pcf for D4 bone. The authors also used PU with a density of 40 pcf in the simulation of the cortical part of the PU blocks. Jin et al.[25] evaluated the effect of cortical bone density on the primary stability of orthodontic mini-implants and used PU blocks consisting of cannellated and cortical parts. They preferred PU foam with densities of 30, 40, and 50 pcf for modelling cortical bone. The authors showed that orthodontic mini-implant stability was associated with increasing cortical bone density. Marchi et al., Elibol et al., Möhlhenrich et al. and Jin et al. used PU foams of different densities to model cortical bone. These studies used PU blocks consisting of trabecular and cortical portions. In contrast to these studies, this study preferred to use PU blocks with a density of 60 pcf to model cortical bone. In the literature, Orhan and Ciğerim[26] preferred a single-layer 60 pcf PU sheet for modelling cortical bone as in this study. The reason for choosing a 60 pcf density PU block was mainly to standardize it with PE. Another reason for our preference was the thought that 60 pcf density would have higher mechanical properties. In support of this idea, Jin et al. showed that the stability of orthodontic mini-implants increased with increasing density of PU foams, and according to this result, increasing the density of PU blocks indicates that the mechanical properties of the blocks also increase.

There is no consensus on the density of PU for modelling cortical bone. No study has evaluated the mechanical properties of the 60 pcf PU blocks used in this study. No study was found using PE blocks for bone modelling in dentistry.

In this study, the flexural strength and hardness values of PE and PU blocks were found to be similar. Since PE blocks have similar properties to PU blocks, which have been accepted for use in mini-implant studies, it shows that PE blocks can be used for bone modelling. The flexural stiffness of cannellous bone was found to be 10-25 MPa and the flexural stiffness of cortical bone was found to be 135-193 MPa.[27] Singh et al.[28] found the average FS of human humerus, ulna and radius to be 128.43, 135.16 and 80.31 respectively and tested corticocancellous bone in their study. The flexural strength of the PE blocks used in this study was found to be 77.85 MPa, which is higher than that of cancellous bone. The flexural strength of the PE blocks used in this study was found to be 77.85 MPa, which is higher than that of cancellous bone. The flexural strength values obtained from the 60 pcf density PE blocks used in this study provide further data to support the use of PE blocks in the modelling of cortical bone. The results of the present study support the use of PE blocks in the in vitro simulation of bone in dentistry. We used PE blocks with a density of 60 pcf to model cortical bone in this study. With their current mechanical properties, we believe that they can be used to model not only cortical bone but also cancellous and corticocancellous bone. As with PU blocks, we recommend that PE blocks are prepared in different densities and used for in vitro modelling of different bone types in orthodontics, oral and maxillofacial surgery and other areas of dentistry.

Limitations

The PE and PU blocks used in the study may have been exposed to different temperature and humidity conditions during manufacture and shipping, which may have affected the test results. In addition, the heat generated during the manufacture of the PE and PU blocks used in the study may have affected the mechanical properties of the blocks to some extent, which may have affected the test results.

The PE and PU blocks used in the study were 60 pcf blocks. In the study, blocks with a single density were preferred and if PU and PE blocks with different densities had been preferred, it is likely that different results would have been obtained in terms of the evaluated mechanical properties of the blocks in terms of FS, EM, and hardness. Therefore, the results obtained are more suitable for interpreting blocks with a density of 60 pcf without generalization.

CONCLUSION

In conclusion, this is the first study to investigate the use of PE blocks for in vitro modelling of jaw cortical bone. It was found that a 60 pcf density PE block had similar properties to a PU block of the same density in terms of flexural strength and stiffness. In addition, the elastic modulus values of the PE block were found to be higher than those of cannellous bone and close to those of cortical bone. These results support the use of 60 pcf density PE in the in vitro modelling of jaw cortical bone. Further studies are needed to investigate the use of different density PE blocks for in vitro modelling of different bone types.

ETHICAL DECLARATIONS

Ethics Committee Approval

Ethics committee approval is not required since this study was conducted on polyethylene and polyurethane blocks in the laboratory.

Informed Consent

Since this study was performed in the laboratory on polyethylene and polyurethane blocks, written consent forms were not obtained.

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Financial Disclosure

The authors declared that this study has received no financial support.

Author Contributions

All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

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