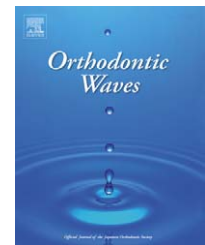


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Research paper

The mechanical properties of dental thermoplastic materials in a simulated intraoral environment

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ABSTRACT

The present study assessed the mechanical properties of dental thermoplastic materials in a simulated intraoral environment. Eight dental thermoplastic products – EVA (Bioplast), PE (Copyplast), PETG (Duran), PP (Hardcast), PC (Imprelon“S”), A+ (Essix A+), C+ (Essix C+), and PUR (Invisalign) – were examined using the following tests: (1) 2-week water absorption test, (2) thickness-change tests with thermoforming and water absorption, (3) tensile tests under room temperature (23 °C) and in a simulated intraoral environment (37 °C). The results were as follows: (1) water absorption increased with time and ranking was (from highest to lowest): PUR, PETG, A+, PC, EVA, PP, C+, and PE. (2) The changes in thickness ranged from 74.9 to 92.6% in comparison with the specimens before thermoforming. Linear expansion with water absorption ranged from 100.3 to 119.9%. (3) The elastic moduli of PC, PETG, and A+ in the simulated intraoral environment showed significant increases in original sheets; in contrast PP, C+, PE, and EVA were significantly reduced. No significant changes were observed in PUR. Tensile yield stress of the specimens in the simulated intraoral environment decreased in comparison with original sheets.

The present result suggests that the mechanical properties of dental thermoplastic materials varied due to environmental factors. Moreover, behavior change is influenced by molecular structure and orientation. The application of thermoplastic materials for orthodontic tooth movement requires a sufficient understanding of the material characteristics, optimal material selection, and design.

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1. Introduction

As thermoplastic materials have excellent esthetic characteristics, are simple to use, and have excellent formability, these materials have been used for orthodontic retainers [1–3] or for minor tooth movement [4–6]. Recently, CAD/CAM technology

has been applied to the design and fabrication of thermoplastic appliances facilitating their use in orthodontic treatment [7–10].

In 1945, Kesling described a tooth positioner fabricated from elastic polymer representing the first time such materials were applied to orthodontic tooth movement [11]. In 1964,

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Nahoum reported a “vacuum-formed dental contour appliance” [12]. Thermoplastic materials have come into general use through the application of thermoforming. The thermoplastic appliances are fabricated on setup models utilizing the elasticity of these materials for controlling tooth movement [4]. However, a new setup model and appliance are required for each tooth movement because of slight tooth movement at the initial setup. Osamu retainers [13,14], designed by Yoshii in 1991, allow an increase in tooth movement at the first appliance fabrication because of a double structure consisting of two materials with different elastic moduli. Essix appliances [5], designed by Sheridan, allow tooth movements with no setup models by providing “divotes” and “windows”. These appliances make it possible to control tooth movements with thermoplastic appliances and reduce the number of technical operations required. However, as they are inferior to edgewise appliances with regard to convenience of use, their application should be limited to minor tooth movement. The Invisalign System [7–10] developed by Align Technology in 1999 allows major tooth movements with thermoplastic appliances by automatically prefabricating a setup model at each stage using CAD/CAM. These clear thermoplastic appliances have attracted a great deal of attention as esthetically more acceptable alternatives to traditional fixed stainless steel appliances. However, there have been few studies of the magnitude of orthodontic forces generated in the mouth with these appliances from a scientific and technological standpoint [15–17].

As thermoplastic polymers are highly viscoelastic materials, temperature, humidity, time after elastic deformation, and forming procedures have marked effects on their mechanical properties [18]. Therefore, the mechanical properties of these materials may differ between the intraoral environment and room temperature. However, the physical values indicated in Material Safety Data Sheet (MSDS) provided by material manufactures comply with the ASTM, DIN, or ISO standards measured under standard atmospheric conditions (23 °C, 50%RH). Therefore, no physical values for these materials in the simulated intraoral environment have been reported. At present, materials are selected for use based on the manufacturer's recommendations, feel, or operator's experience.

In the present study, we compared the mechanical properties of different thermoplastic materials under room temperature (23 °C) with those in a simulated intraoral environment

(37 °C) to determine the orthodontic forces generated by thermoplastic materials in the mouth.

2. Materials and methods

Eight thermoplastic products used for orthodontic appliances were evaluated, as listed in Table 1.

2.1. Water absorption test

Three specimens measuring 20 mm × 20 mm were prepared from each material prior to thermoforming. The specimens were stored in a desiccator to reach a constant weight (M1), and then immersed in distilled water at 37 °C. After a predetermined time, water on the specimens was wiped off with a cloth, and the weight (M2) of each specimen was determined with a sensitive digital balance (Mettler AE240, Sartorius, Germany) within 1 min. Water absorption was calculated as $(M2 - M1) \times 100/M1$ (wt%). After the beginning of immersion, the water absorption rates at 1, 3, 6, 12, 24, 48, 72, 168, and 336 h were determined to calculate the mean values. Comparisons of water absorption rates after 24 and 336 h were made using an analysis of one-way ANOVA and Schéffe's multiple comparison test.

2.2. Measurement of changes in thickness of the thermoplastic materials with thermoforming and water absorption

Rectangular specimens (length = 40 mm, width = 5 mm) were cut from each sheet before and after thermoforming. The sheets were formed on a stone block (New plastone, GC Co., Tokyo) in 10 mm thickness with a positive pressure thermal forming machine (Biostar, Scheu-Dental, Germany) according to the temperature and compression time recommended by manufacturer. The materials that required preliminary drying were heated beforehand with a drying oven (Drying oven, Scheu-Dental, Germany). After conditioning for 24 h at room temperature, the thickness of each specimen before and after thermoforming was measured with a digital micrometer (CD-15CPX, Mitutoyo Co., Kanagawa). The laboratory environment was 23 °C and 50% relative humidity. After thermoforming, the specimens were immersed in distilled water at 37 °C to

Table 1 – Materials used in this study

Code	Thickness	Product name	Manufacturer	Component (MSDS)
EVA	1.0 mm	Bioplast	Scheu-Dental, GmbH	Ethylene–vinyl acetate copolymer
PE	1.0 mm	Copyplast	Scheu-Dental, GmbH	Polyethylene
PETG	1.0 mm	Duran	Scheu-Dental, GmbH	Polyethylene terephthalate glycol
PP	0.8 mm	Hardcast	Scheu-Dental, GmbH	Polypropylene
PC	0.75 mm	Imprelon “S”	Scheu-Dental, GmbH	Polycarbonate
A+	0.040 in.	Essix A+	Raintree Essix, Inc.	Copolyester
C+	0.040 in.	Essix C+	Raintree Essix, Inc.	Polypropylene/ethylene copolymer (>95%), stabilizers (<5%)
PUR	0.030 in.	Invisalign	Align Technology, Inc.	Polyurethane from methylene diphenyl diisocyanate and 1,6-hexanediol, Additives

Component as obtained from the manufacturers' Material Safety Data Sheet.



Fig. 1 – Universal testing machine and constant-temperature zone used for tensile test.

measure their thickness. The soaking time into distilled water was set as 24 h, assuming the removal of clinical orthodontic appliances. The mean values and standard deviations of eight specimens were calculated.

2.3. Tensile test

Rectangular specimens 5 mm in width and 40 mm in length were used for tensile tests. The cross-sectional area of each specimen was determined with a micrometer (CLM1-15QM, Mitutoyo Co., Kanagawa) and thermoforming was performed according to the method described above. The tests were performed under the following three conditions and the results were compared.

- (1) Prior to thermoforming, the specimens were conditioned at room temperature (23 °C) for 24 h and tested under the same conditions.
- (2) After thermoforming, the specimens were conditioned at room temperature (23 °C) for 24 h and tested under the same conditions.
- (3) The simulated intraoral environment: after thermoforming, the specimens were immersed in distilled water at 37 °C for 24 h and tested at 37 °C.

Tensile tests were performed with a compact universal testing machine (Texture Analyser, EKO instruments Co., Tokyo) set in a constant-temperature zone (Fig. 1). Six or more specimens per material were tested under each condition. The distance between points was defined as 10 mm, and the crosshead speed was defined as 0.2 mm/s to obtain stress-strain curves. The elastic modulus (tangential elastic modulus) and tensile yield stress were calculated from the obtained stress-strain curves. The mean value and standard deviation of each item were also determined. Comparisons among materials under each test condition and with regard to elastic modulus and tensile yield stress of the specimens after thermoforming (in the simulated intraoral environment) were performed by one-way ANOVA and Schéffe's test.

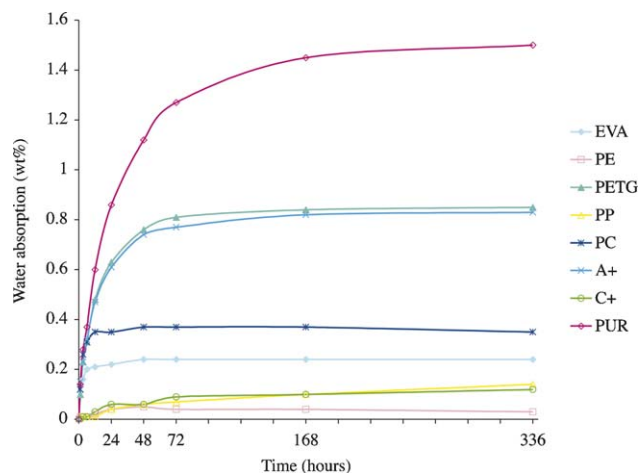


Fig. 2 – Water absorption up to 2 weeks of eight thermoplastic products.

3. Results

3.1. Water absorption properties

Table 2 shows the sequential changes and standard deviations of water absorption rates up to 2 weeks. The water absorption rates are shown graphically in Fig. 2.

Water absorption of all products increased with time, and EVA, PE, and PC reached a plateau during the measurement period. Of all the materials examined, PUR showed the highest water absorption after both 24 and 336 h ($P < 0.01$) and a higher value of 1.50 wt%, despite not reaching the saturation point within the measurement period. PETG and A+ showed higher values of water absorption; there were no significant differences between these materials after either 24 or 336 h. The water absorption rates of EVA and PC were significantly different from those of the other materials after both 24 and 336 h ($P < 0.05$). PE had the lowest water absorption value, with a rate of 0.03 wt% after 336 h. There were no significant differences between PE and PP or C+ at 24 h after the beginning of water absorption; however, these materials did not reach the saturation point, and significant differences were observed between PE and PP or C+ after 336 h ($P < 0.05$). There were no significant differences between PP and C+.

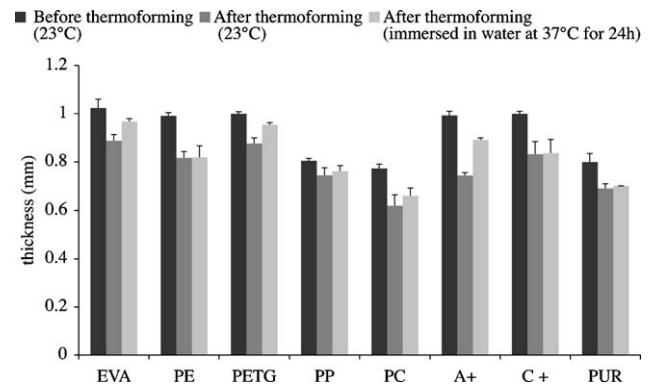
3.2. Thickness-change tests with thermoforming and water absorption

Table 3 and Fig. 3 show the changes in thickness of the specimens before thermoforming at 23 °C, those after thermoforming at 23 °C, and those after thermoforming immersed in distilled water at 37 °C for 24 h.

The changes in thickness with thermoforming ranged from 74.9 to 92.6% relative to the original dimensions, and the linear expansion with water absorption ranged from 100.3 to 119.9%. PE showed the smallest linear expansion rate. The materials were ranked as follows, from lowest to highest: PE, C+, PUR, PP, PC, PETG, EVA, and A+.

Table 2 – Water absorption after storage in water at 37 °C for specified period

Material	1 h		3 h		6 h		12 h		24 h (1 day)		48 h (2 days)		72 h (3 days)		168 h (1 week)		336 h (2 weeks)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
EVA	0.11	0.04	0.16	0.05	0.20	0.02	0.21	0.02	0.22	0.02	0.24	0.01	0.24	0.01	0.24	0.01	0.24	0.01
PE	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.04	0.03	0.05	0.02	0.04	0.03	0.04	0.05	0.03	0.03
PETG	0.10	0.00	0.23	0.01	0.31	0.01	0.48	0.01	0.63	0.01	0.76	0.00	0.81	0.01	0.84	0.00	0.85	0.01
PP	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.04	0.01	0.06	0.05	0.07	0.03	0.10	0.02	0.14	0.00
PC	0.12	0.02	0.26	0.02	0.31	0.03	0.35	0.06	0.35	0.03	0.37	0.02	0.37	0.02	0.37	0.02	0.35	0.04
A+	0.15	0.08	0.23	0.02	0.32	0.03	0.47	0.02	0.61	0.01	0.74	0.02	0.77	0.02	0.82	0.02	0.83	0.03
C+	0.00	0.00	0.01	0.02	0.01	0.02	0.03	0.03	0.06	0.00	0.06	0.00	0.09	0.02	0.10	0.03	0.12	0.02
PUR	0.14	0.01	0.28	0.05	0.37	0.01	0.60	0.01	0.86	0.01	1.12	0.04	1.27	0.01	1.45	0.05	1.50	0.03

**Fig. 3 – Change in thickness under the three conditions.**

3.3. Tensile properties

3.3.1. Stress-strain curve

The obtained stress-strain curves are shown in Fig. 4.

- (1) Before thermoforming (23 °C): tensile tests of specimens before thermoforming at room temperature (23 °C).

The stress of PETG, A+, and PUR exceeded the upper limit of the testing machine used (245 N), and no tensile yield stress could be determined for these materials. The tensile yield stress of PC showed a definite peak on the stress-strain curve, while those of PP and C+ showed shallow peaks. For PE and EVA, a curve to yield elongation was shown with no peak; these materials showed lower tensile yield stress.

- (2) After thermoforming (23 °C): tensile tests of specimens after thermoforming at room temperature (23 °C).

The tensile yield stress of PETG, A+, and PUR showed a clearly defined peak similar to PC.

- (3) After thermoforming (37 °C): tensile tests of specimens after thermoforming immersed in distilled water at 37 °C for 24 h and tested at 37 °C.

Although the stress-strain curves of all materials showed the same tendency as the specimens after thermoforming under room temperature.

3.3.2. Elastic modulus and tensile yield stress

The elastic modulus and tensile yield stress were calculated from the stress-strain curves; the values are shown in Figs. 5 and 6, respectively, for each condition.

3.3.2.1. Elastic moduli under each condition. No significant changes were observed for PUR, while PC, PETG, and A+ specimens after thermoforming (23 °C) and those after thermoforming (37 °C) showed significant increases of elastic modulus as compared to those before thermoforming (23 °C). The specimens after thermoforming (37 °C) of PP, C+, PE, and EVA showed significant reductions of elastic moduli as compared to those before thermoforming (23 °C). While the specimens of C+ after thermoforming (23 °C) showed sig-

Table 3 – Mean and standard deviation of thickness under each condition

Material	Before thermoforming (23 °C)		After thermoforming (23 °C)			After thermoforming (immersed in water at 37 °C for 24 h)		
	Mean (mm)	S.D.	Mean (mm)	S.D.	Ratio of after/before thermoforming (%)	Mean (mm)	S.D.	Ratio of after/before water absorption (%)
EVA	1.02	0.04	0.89	0.03	86.7	0.97	0.01	109.0
PE	0.99	0.01	0.82	0.03	82.4	0.82	0.05	100.3
PETG	1.00	0.01	0.88	0.02	87.7	0.95	0.01	108.8
PP	0.80	0.01	0.74	0.03	92.6	0.76	0.02	102.3
PC	0.77	0.02	0.62	0.04	80.2	0.66	0.03	106.5
A+	0.99	0.02	0.74	0.01	74.9	0.89	0.01	119.9
C+	1.00	0.01	0.83	0.05	83.2	0.84	0.06	100.5
PUR	0.80	0.04	0.69	0.02	86.4	0.70	0.00	101.4

The thickness ratio of the specimens after thermoforming (23 °C) to those before thermoforming (23 °C) represents forming shrinkage. The thickness ratio of the specimens after thermoforming (immersed in water at 37 °C for 24 h) to those after thermoforming (23 °C) represents hygroscopic expansion.

nificant increases of elastic moduli as compared to those before thermoforming (23 °C), the elastic modulus values of PP, PE, and EVA decreased significantly after thermoforming (23 °C).

3.3.2.2. Tensile yield stress under each condition. The tensile yield stress of the specimens of PETG, A+, and PUR before thermoforming (23 °C) could not be measured as they exceeded the upper limit of the testing machine used. However, the specimens after thermoforming (23 °C) and those after thermoforming (37 °C) showed definite decreases in tensile yield stress as compared with those before thermoforming (23 °C). The specimens after thermoforming (23 °C) and those after thermoforming (37 °C) of other materials showed significant reductions in tensile yield stress as compared to those before thermoforming (23 °C).

3.3.3. Differences in mechanical properties among materials in the simulated intraoral environment

Figs. 7 and 8 show the properties of the materials examined in this study.

- (1) Significant differences were found in the elastic modulus among materials, except for two combinations (PETG and A+, and PP and C+; $P < 0.01$). The ranking of elastic moduli in the intraoral environment, from highest to lowest, was as follows: PC, PETG and A+, PUR, PP and C+, PE, and EVA.
- (2) Three combinations, PC and PUR, PETG and A+, and PP and C+, showed no significant differences in tensile yield stress. Thus, the ranking of tensile yield stress in the intraoral environment, from highest to lowest, was as follows: PC and PUR, PETG and A+, PP and C+, PE, and EVA.

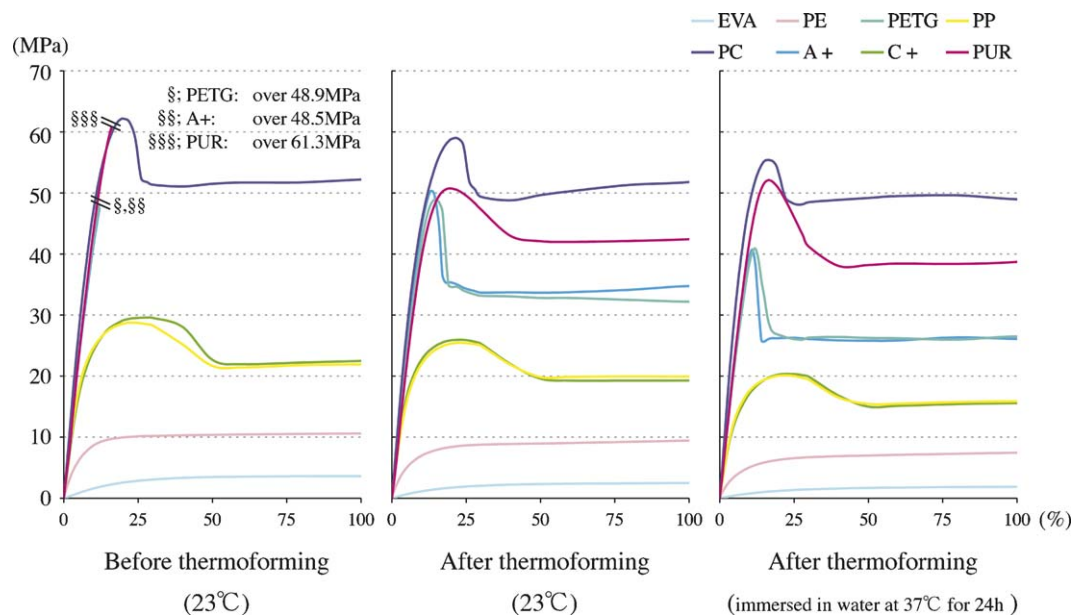


Fig. 4 – Stress-strain curves of specimens before thermoforming (23 °C), specimens after thermoforming (23 °C), and specimens after thermoforming (immersed in water at 37 °C for 24 h) under the three conditions. The stress of specimens of PETG, A+, and PUR before thermoforming exceeded the upper limit of the testing machine used.

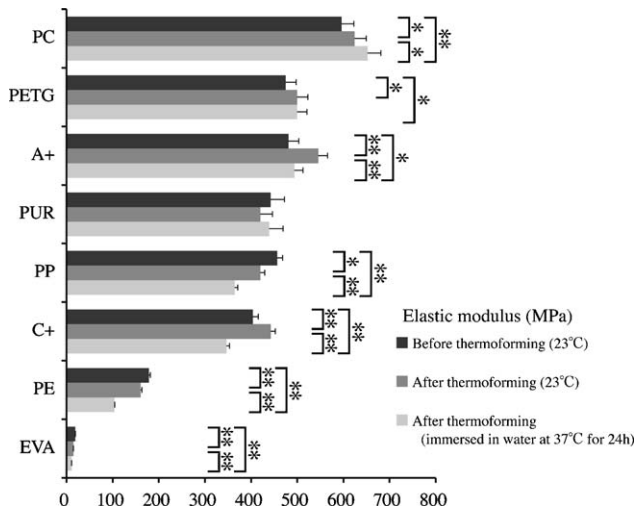


Fig. 5 – Comparison of elastic moduli under each condition. Statistically significant differences: * $P < 0.05$, ** $P < 0.01$; Scheffé's test.

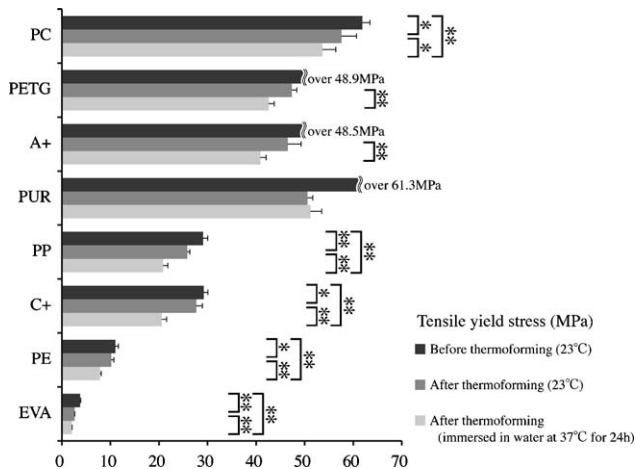


Fig. 6 – Comparison of tensile yield stress under each condition. Statistically significant differences: * $P < 0.05$, ** $P < 0.01$; Scheffé's test.

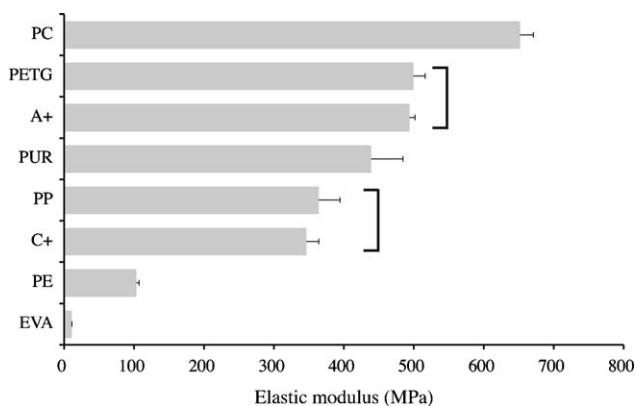


Fig. 7 – Comparison of elastic moduli among materials in the simulated intraoral environment. The solid black line connects values that are not significantly different at $P = 0.01$.

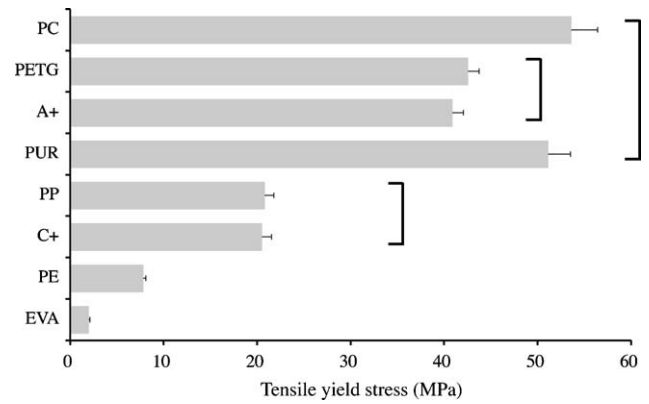


Fig. 8 – Comparison of tensile yield stress among materials in the simulated intraoral environment. The solid black line connects values that are not significantly different at $P = 0.05$.

4. Discussion

The mechanical properties of thermoplastic materials are influenced by both structural factors, such as molecular and crystal structures, and environmental factors, such as temperature, humidity, pressure, and heat history [18]. Therefore, the mechanical properties vary under the influence of both forming conditions and the conditions of use.

Structurally, polymer materials are either amorphous or partly crystalline. Many amorphous plastics are clear because visible light can pass through polymers. In contrast, many crystalline plastics are opaque because they contain mixtures of crystalline and amorphous polymers with different refractive indexes. Understanding of crystal structures requires thermal analyses, X-ray diffraction, and density analyses. In the present study, PC, PETG, A+, and PUR were classified to be amorphous plastics, while PP, C+, PE, and EVA were taken to be crystalline plastics based on their melting points. These mechanical properties vary rapidly with temperature over the range of glass transition. Plastics solidify to a glass at temperatures lower than the glass transition temperature (T_g), but soften rapidly on exceeding T_g . The changes in the mechanical properties at this point differ significantly between amorphous and crystalline plastics. While crystalline plastics at T_g remain intact and firm, amorphous regions with weak intermolecular forces move. Therefore, the mechanical properties vary according to the degree of crystallinity. In contrast, as amorphous plastics have no crystalline regions, they become soft and flexible elastomers or highly viscous liquids above T_g . Therefore, in the stress-strain curves of the specimens before thermoforming obtained in the present study, the T_g of PC, PETG, A+, and PUR, which showed steep initial increases, i.e., high elastic moduli, is above room temperature, while that of PP, C+, PE, and EVA, which showed gentle initial increases, is below room temperature. The mechanical properties of materials with T_g below room temperature may be influenced markedly by changes in temperature.

In addition, polymer materials may have molecular orientation depending on the processing methods and conditions used. Molecular orientation confers physical properties, on anisotropic materials which generally have multiple elastic moduli [18,19]. For example, horizontal loads on molecular orientation show a higher elastic modulus than vertical loads. Further, the mechanical properties may vary depending on the thermoforming conditions and use conditions, such as application in the presence of saliva and the creep phenomenon.

4.1. Influence of water absorption

Polymer materials absorb water through humidity in the air or immersion in water, and water absorption generally causes expansion and changes in the mechanical properties of such materials. The intraoral changes in dimension with hygroscopic expansion may affect the fit of appliances fabricated from such materials resulting in changes in orthodontic forces.

The results of the present study indicate that amorphous plastics have higher water absorption rates, while crystalline plastics have lower water absorption rates. PUR showed the highest water absorption rate. Water absorption phenomena are caused by attachment of water molecules on the material surface and their subsequent absorption or binding into materials. However, extrapolating molecular structures of the materials used in the present study from MSDS showed that none of the materials contained hydrophilic groups. The absorption of water into materials is dependent on the free volume. Consequently, crystalline plastics with high molecular densities showed lower water absorption rates, while amorphous plastics without crystalline regions showed higher water absorption rates due to the large free volume.

In the present study, measurements were made at room temperature to determine changes in the dimensions of the specimens with water absorption under clinical conditions. The water absorption tests were performed from a constant weight. Therefore, while the materials with higher water absorption rates tended to show hygroscopic expansion, there was no direct correlation between the water absorption rate and the hygroscopic expansion volume under these conditions. PUR, which had the highest water absorption rate, showed a lower rate of hygroscopic expansion. This material was considered to have already absorbed large amounts of moisture and to have undergone marked hygroscopic expansion at room temperature.

Our observations suggest that use of these polymer materials for fabrication of orthodontic appliances requires a clear understanding of the dimensional changes that occur under simulated intraoral conditions.

4.2. Influence of thermoforming

The rates of change in the dimensions of original sheets 1, 0.8, and 0.75 mm in thickness ranged from 74.9 to 87.7%, 86.4 to 92.6%, and 80.2% of full size, respectively. The thermoforming procedures in the present study were performed under the respective manufacturer's recommended conditions. How-

ever, the changes in thickness with thermoforming had no direct relationship with the thickness of the original sheets. The thickness after thermoforming is considered to be profoundly influenced by differences in temperature between the heating temperature and the melting points of crystalline plastics or the softening points of amorphous plastics, heating time, and molecular weight. Therefore, the shrinkage rates varied between the different materials. In addition, as changes in thickness have an effect on dynamic properties, the effects on use of these materials as orthodontic appliances should be considered.

Changes in mechanical properties before and after thermoforming were also determined. Crystalline plastics generally show an increase in the degree of crystallinity with thermoforming, and therefore the values of elastic modulus and tensile yield stress for such materials should increase [18]. However, with the exception of C+, the crystalline plastics examined in the present study showed decreases in both tensile yield stress and elastic modulus. With the exception of PUR, amorphous plastics with no crystalline regions showed reductions in tensile yield stress and increases in elastic modulus. These observations seemed to be due to differences in the molecular orientation of each specimen. The decrease in molecular weight with heating could have caused the observed decreases in mechanical properties [18]. The crystalline plastics used in the present study contain no benzene rings, and therefore the molecular weight would be decreased. Addition of a stabilizer, which would control the decrease in molecular weight with heating, is described in the MSDS only for C+. If the degree of crystallinity is increased by heating, the mechanical properties should also increase. However, the rapid cooling after heating, such as the cooling times recommended by the manufacturers, makes it difficult for crystallization to develop. Therefore, as C+ showed a small effect of a decrease in molecular weight, its mechanical properties may have increased under the influence of slight crystallization. For the other materials tested, the mechanical properties may have decreased under the influence of the decrease in molecular weight. Further studies using methods such as thermal analysis are required to characterize these changes in molecular structure that occur with processing.

4.3. Simulated intraoral environment

The mechanical properties of thermoplastic materials in the mouth are influenced by thermoforming, water absorption, and temperature. No significant differences were found in the elastic moduli of the simulated intraoral environment between PETG and A+ or between PP+ and C+, most likely because these materials have very similar molecular structures. No significant differences were observed in tensile yield stress between PC and PUR, PETG+ and A+, or between PP and C+. Materials with a high elastic modulus commonly have high tensile yield stress. PUR showed higher tensile yield stress in comparison with its elastic modulus. As polymer materials are influenced by creep phenomena, it is inadequate to simply determine the region up to tensile yield stress as the elastic deformation zone. However, as PC, which that showed the same tensile yield stress level as PUR,

showed the highest elastic modulus, PUR is a highly resilient material.

The materials in the group that showed definite yield points on the stress-strain curves (PC, PETG, A+, and PUR) had higher elastic moduli and are all amorphous plastics. In the comparison of elastic moduli of the specimens after thermoforming, PC and A+ varied, but PETG and PUR did not vary significantly. PC, PETG, and A+, with the exception of PUR, showed decreases in tensile yield stress. These four materials in this group have benzene rings in their molecular structures and have high elastic moduli. From these characteristics, the T_g values of these four materials are much higher than the simulated intraoral temperature. Therefore, the changes in temperature from 23 to 37 °C will have little influence on their mechanical properties. At the same time, these materials also showed high rates of water absorption. The magnitudes of the effects of water absorption on the mechanical properties differ between materials. Those for which the mechanical properties varied in the simulated intraoral environment would be influenced by water absorption.

For the group that showed gentle yield points on the stress-strain curves (PP and C+), the specimens after thermoforming in the simulated intraoral environment showed significant decreases in both elastic modulus and tensile yield stress as compared to those after thermoforming under room temperature. These materials were crystalline plastics and showed lower water absorption and lower T_g . Water absorption would have little influence on the mechanical properties of these materials. In addition, as the room temperature already exceeds T_g , slight changes in temperature from 23 to 37 °C would have marked effects on the mechanical properties of these materials.

Ultimately, the materials belonging to the group that showed no definite yield points (PE and EVA) were crystalline plastics, and their mechanical properties varied in the simulated intraoral environment. With the lowest elastic moduli and tensile yield stress, these materials seem to have lower T_g and would be profoundly influenced by changes in temperature show significant decreases in their mechanical properties.

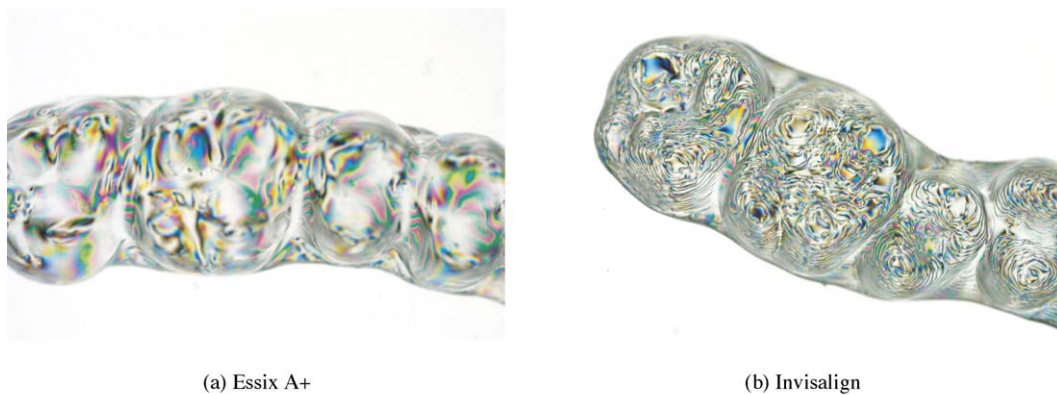
5. Conclusion

Clear plastic materials had higher elastic moduli and water absorption rates, and the change in temperature from 23 to 37 °C will have little influence on their mechanical properties. The intraoral changes in dimension with hygroscopic expansion may affect the fit of appliances fabricated from such materials resulting in changes in orthodontic forces. In contrast, opaque materials had lower elastic moduli and water absorption rates, and slight changes in temperature from 23 to 37 °C would have marked effects on their mechanical properties.

The results described above suggest that the magnitudes of the effects of changes in temperature and water absorption on the mechanical properties of thermoplastic materials in the simulated intraoral environment differ between different materials. Therefore, materials should only be selected for use in orthodontic appliances after detailed characterization of their mechanical properties in the simulated intraoral environment.

The mechanical properties of thermoplastic materials used for tooth movement differ according to processing history and environment of use. Further complex changes occur clinically under the influence of viscoelasticity and form. The molecular structures adopt different molecular orientations according to processing history. Fig. 9 shows the molecular orientations of orthodontic appliances fabricated from thermoplastic materials. The molecular orientation also affects the mechanical properties of thermoplastic materials. To understand the orthodontic forces influenced by these properties, measurements must be made on dentition models under simulated clinical conditions, using an experimental dynamic method and a computational dynamic method.

The present study suggests the possibility of changes in the mechanical properties of thermoplastic materials. We will discuss the relationship between the molecular orientation and the mechanical properties of these materials in future reports.



Polarized photo of after thermoforming

Fig. 9 – Polarized photographs of dental arch-shaped thermoformed thermoplastic materials. The molecular orientation within the material can be determined from the interference patterns.

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